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THE INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH AND INNOVATION EDITORS

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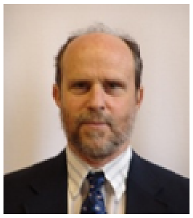

Philip Weinsier, IJERI Manuscript Editor

IN THIS ISSUE

In this issue, we take you from the heart of the Swedish manufacturing industry to the healthcare industry; from a study of the minds of babies to the use of solar energy in robotics. Lean manufacturing, or simply Lean, is a concept of reducing the expenditure of resources that do not have a direct impact on a product or its value. The more traditional application of the Lean principles were applied by Swedish researchers in their study of investing in robotic automation by the Swedish manufacturing industry for purposes of remaining competitive in the world market. Another article in this issue superimposes the processes of Lean on the healthcare industry in order to evaluate current processes and to improve the overall efficiency of clinics; specifically to maximize throughput, minimize wait time, minimize flow (transportation) and maximize utilization of nurses and providers. And while all of these projects are current and likely will have significant impacts in their respective fields, what stands out for me in this issue is a study of swarming as it applies to packs of nearly identical robots.

Researchers have for some time now studied the cohesive attributes of insect swarms and the intelligence, or lack thereof as most of us would attribute to an insect, that seems to be inherent to them when they gather and swarm. And what generally would seem a simple, logical plan for an individual insect, suddenly becomes an intellectually charged pack with a synergistic increase in cohesiveness. According to the authors of this study (see *Test-Bed Development of Shared-Mission Autonomous Ground/Aerial Dissimilar Swarming* on page 20), A team at the University of Southern California is taking a bio-mimicry approach to the control of each member of the swarm, while researchers at the University of Karlsruhe in Germany are focusing their efforts on sending a large team of centimeter-scale robots to explore and colonize mars.

One fascinating aspect of such research is that despite the failure of one robot—or death of an individual insect—the swarm itself is able to continue, seemingly unhindered in its quest. Like the German group, a team at the University of Essex in the United Kingdom is working on a “flock” of quadrotor helicopters that they call Owls. Adding to the swarm’s ability to focus all of its members, the Owls have gone a step further to allow each member of the group to share its data and processing power with the others, again, to realize the old adage: All for one and one for all!

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IAJC conferences have been a great success, with the main conferences being held in the United States and regional, simultaneous conferences, in other parts of the world. IAJC attracts myriad journals that wish to publish the best of what its attendees have to offer, thereby creating excitement in academic communities around the world. IAJC is a first-of-its-kind, multilayered umbrella consortium of academic journals, conferences, organizations and individuals committed to advancing excellence in all aspects of technology-related education.

IJME is steered by IAJC’s distinguished Board of Directors and is supported by an international review board consisting of prominent individuals representing many well-known universities, colleges, and corporations in the United States and abroad.

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Listed here are the members of the IAJC International Review Board, who devoted countless hours to the review of the many manuscripts that were submitted for publication. Manuscript reviews require insight into the content, technical expertise related to the subject matter, and a professional background in statistical tools and measures. Furthermore, revised manuscripts typically are returned to the same reviewers for a second review, as they already have an intimate knowledge of the work. So I would like to take this opportunity to thank all of the members of the review board.

As we continually strive to improve upon our conferences, we are seeking dedicated individuals to join us on the planning committee for the next conference—tentatively scheduled for 2013. Please watch for updates on our website (**www.IAJC.org**) and contact us anytime with comments, concerns or suggestions. Again, on behalf of the 2011 IAJC-ASEE conference committee and IAJC Board of Directors, we thank all of you who participated in this great conference and hope you will consider submitting papers in one or more areas of engineering and related technologies for future IAJC conferences.

If you are interested in becoming a member of the IAJC International Review Board, send me (Philip Weinsier, IAJC/IRB Chair, philipw@bgsu.edu) an email to that effect. Review Board members review manuscripts in their areas of expertise for all three of our IAJC journals—IJME (the International Journal of Modern Engineering), IJERI (the International Journal of Engineering Research and Innovation) and TIIJ (the Technology Interface International Journal)—as well as papers submitted to the IAJC conferences.

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LEAN ENTERPRISE PRINCIPLES APPLIED TO HEALTHCARE

Kambiz Farahmand, North Dakota State University; Reza Karim, North Dakota State University; Raghavan Srinivasan, North Dakota State University; Reza Sajjadi, North Dakota State University; Lori Fisher, Fargo VA Medical Center

Abstract

In this study, a discrete event simulation model was developed in order to evaluate current processes and to improve the overall efficiency of the clinic. The performance measures considered were maximizing throughput, minimizing wait time, minimizing flow (transportation) and maximizing utilization of nurses and providers. The virtual simulation model was developed using ARENA software Version.12 (Rockwell Automation Technologies, Inc). From the comparison of the results, it was observed that moving the exam room of the busiest provider closer to the waiting area achieved a considerable reduction (8.5%) in the yearly distance traveled, from the patient's perspective. Changing the location of nurses and providers when compared with the current scenario resulted in a reduction of 18% for the total distance traveled by the patients in any given year. Assigning one nurse to each provider when compared with the current scenario resulted in an 8.48% reduction in the total distance traveled by the patients. The analysis indicated that by improving overall space utilization, the utilization rates for exam and procedure rooms were increased where it subsequently improved the flow of patients and equipment.

Introduction

Clinic space utilization was studied from the aspect of Lean Healthcare. The goal of the study was to develop a simulation model which can be readily adapted to the large variation in clinic structures that maximizes efficiency and workflow within the constraints of existing architectural limitations. Variations in mode of operation and space utilization were observed believed to be based on inefficient flows and lack of standardized layout. There is an increasing demand for both capacity and service quality in healthcare. Studies show that clinic examination rooms are idle for a significant part of the patient care cycle. Studying patient flow characteristics throughout a facility based on need provides insight into optimizing space use. The authors set out to develop an idealized clinic layout that would maximize clinic efficiency and work flow and could be used as an initial platform layout to launch future clinical space designs. To increase the utilization of space, resources, and equipment, and to increase the patient throughput without sacrificing quality care, seven flow designs were identified in the clinic: patients, staff, information, equipment, supplies, diagnostic tests and procedures, as well as medications. The simulation model was built considering flow of patients, staff and information. Arena software was used to develop the simulation model. This project was conducted in the VA Medical Center.

Literature Review

An in-depth literature review was conducted in the areas of Lean Applications and Operations Research (OR) concerning space utilization and optimization of healthcare facilities. Benninger and Strode [1] developed a methodology for maximizing efficiency of staff and resources which was simulated in the general Otolaryngology department. The authors measured total clinic time, number of patients seen, patient waiting time, physician and nurse productivity, and examining-room use. The simulation showed that there were increases in physician time spent with patients, and a reduction of patient waiting time.

Eneyo [2] used simulation software to design the new unit taking into consideration production and assembly activities, which are subject to the future expansion of the company. The design of the new facility was conducted in four phases: 1) Data collection, 2) Simulation of existing conditions, 3) Simulation of an expansion phase, and 4) Layout development of the new facility.

Joseph [3] employed the lean methodology in designing the layout of a laboratory. This was done in order to design an optimal facility layout which would have a smooth process flow, minimized handling distances, reduced walking distances, and improved visibility for effective management of operations, enhanced work environment and better inventory management. The first step here was to study the existing state of operations in the process including measurement of cycle time, lead time and TAT time (task time). The next step led to implementation of lead strategies such as proposing a U-shaped design that would minimize operator walking. This was followed by a projection of growth for the future. Based on the results, predicted values of space requirements were developed for each of the units. The next step involved the development of a high-level layout using optimization. This was done in four steps: Quantify all work flows, workflow weights, flow matrix and layout optimization. Based on these optimizations, layouts were drawn and evaluated. These block diagrams of the space layout were then modified into detailed drawings. Implementation of lean culture and mock-ups were integrated into the detailed planning. The lean design resulted in an efficient design that optimizes specimen flow, increases staff productivity and reduces waste throughout the life of the facility. The lean process improvement as applied to healthcare settings needs to be studied more in depth and feedback of patients should also be incorporated into the analysis so as to gain efficiency related to patient flow and patient satisfaction.

Eric [4] applied lean concepts to the Emergency Department (ED) and looked for improvement in service delivery by emergency–care personnel. The measurement of satisfaction of patient visits was conducted before and after the implementation of lean techniques for a period of one year. The authors applied a six-step process of lean education, made observations of the emergency department, analyzed patient flow, redesigned the process based on findings, and developed new testing procedures that could be implemented in the ED. Outcomes were measured using patient satisfaction, expense per patient, length of stay (LOS) in the emergency department and patient volume. These outcomes were compared for 2005 data (before) and 2006 data (after). Lean concepts were tested to see if the implementation of the fundamental change of thinking improves patient satisfaction as well as staff satisfaction. A change-of-thinking requirement was developed due to the demands of safe, efficient and quality-driven needs in the healthcare system. Lean concepts from the Toyota Production System (TPS), if applied to healthcare, indicate that clinic personnel need to care for patients. A lean team is first formed from all departments. The processes involve process mapping and then assessing the amount of waste using value-stream mapping (VSM). VSM documents the time taken in each step with the arrival of each patient and quantifies time at different steps as value-added or not value-added. From here, the determination is made which step adds value to the patient experience and which step takes up resources and time and incurs cost without adding value. Then, the lean team determines if all steps involved in the patient visit are required and redesigns the process by modifying or eliminating the waste. This newly developed process was tested and implemented with continuous feedback for improvement from the frontline staff that has more insight of the process. In non-lean environments, reduction of cost is emphasized. In lean environments, quality and flow are evaluated first; when these are improved in current staff, synchronization of staff can then be focused on after which factors of efficiency can be evaluated. It was found that lean improved the value of care to the patient. The end result of applying lean in healthcare was a higher-value product when compared with one produced using a management style analysis focusing on single-step efficiency. One of the findings in this study was an increase of 9.23% in patient visits.

Cote [5] described patient flow and resource utilization under an individual physician in primary health care. An analysis of service (time a patient spent in consulting) and sojourn (total time spent at some location in the clinic) was conducted. A discrete-event simulation model was constructed in order to find the relationship between examination room capacity and patient flow across four clinic-based performance measures.

Hasson et al. [6] conducted a study of methodological issues in nursing research such as preparation, action steps and difficulties that are inherent within the Delphi technique. There were issues in identifying the problem, research skills to conduct the investigation and data presentation. The authors studied these problems. Reliability of this method was based on the assumption that several people were less likely to come to a wrong conclusion. The validity of this method was enhanced by a reasoned argument in which assumption were challenged. Findings from Delphi study helped to streamline the work. Baker [7] utilized mathematical modeling in a teaching clinic to improve patient care. The model was used in the planning and decision-making process establishing a relationship between physicians, time and space.

Feyen et al. [8] studied workflow of a clinic in the VA medical center in Indianapolis. The process here involved discussion with the staff, data collected on the current workflow for a week, current room utilization and any other time data. A Gantt chart was developed to evaluate usage of each room each day. Three specific approaches were considered to improve room management. AutoMod was used to analyze workflow. Authors implemented movement monitoring systems in each room, utilizing notification systems and using computers in the nurses' station. Physical room layout was analyzed. Through VA staff input and general industrial engineering principles, it was determined that changes such as putting in additional walls, doorways and shelving units would reduce unnecessary time and improve room management. The authors were informed about several areas that contributed to inefficient room management. The room assignments were handled arbitrarily, resulting in inefficient use of rooms.

Gibson [9] used a discrete-event simulation tool for the purpose of planning and designing of the hospital building.

The approach began with the problem formulation phase of setting the objectives and developing a project plan based on the Baldridge National Quality Program for the healthcare sector. In the planning phase, a value management study which considers the information process mapping and workplace study information was taken into account to reduce cost of service while improving and maintaining quality. The next step involved the simulation of the planning phase for which real-time data were collected. Next came the master planning phase where resources such as waiting area and reception would be taken into account. The last and final step considered the schematic design phase which involved preparation of architectural and engineering drawings.

Miller et al. [10] studied the new hospital space allocation and schedule configuration design using tools-simulation, linear programming and spreadsheet analyses. A new 600-bed hospital for women and children was being constructed at the hospital facility to replace the existing one. The requirements as summarized by the author were to a) maintain a large number of specialty and sub-specialty outpatient services, b) maintain significantly less space to house these services in the new facility, and c) meet complex scheduling requirements, both clinically and operationally, due to teaching requirements. The current structure was completely studied using process maps, and future requirements/ constraints were noted. Parameters were set up by the design team, including number of exam rooms and number of clinics. The next step after making initial assumptions was data collection, the last step prior to simulation. The data here were collected by observing the process and gathering information from the hospital staff, after which the data were analyzed. A multi-faceted approach consisting of modeling, linear programming and discrete event simulation was used to predict and forecast future behavior. For the purpose of validating the model, the software developers ensured that the models would behave similar to the real system. Two types of models were studied here. Various scenarios were simulated with different clinic configurations. Several iterations of the models were performed in order to determine the optimal location. The decision was made after the service department and the project team reached a conclusion. The results did not show an optimal solution but yielded a more realistic and practical solution. This analysis of high-level and low-level model led to a better and optimized utilization of the space. Stake holders' input was taken into account after the results but prior to implementation.

Based on a review of the literature, a wide array of issues within the healthcare delivery system were observed that included inefficient space utilization, unnecessary travel time of clinic staff and patients, improper allocation of rooms, and lack of desired equipment and capacity constraints for space. To improve these issues, discrete event simulation and lean concepts were applied. Review of specific case studies that were developed in numerous healthcare clinic settings found that simulation was used to examine bottlenecks and to improve utilization and access. Lean techniques such as Six Sigma, Five S, and Value Stream Mapping were also widely used by management to improve the level of service. It was also observed that a number of researchers stressed the importance of gathering reliable and comprehensive information about the system being studied, and the obvious solution was to interview and/or survey the individuals interacting with the given clinical setting [11].

Numerous strategies such as RFID, bar-coding and videotaping were considered for data collection and field observation, but due to time constraints, interviews, questionnaires and on-site observation were selected as the primary modes to gather data. Face-to-face interviews with staff provided an understanding of the standard operating process and the type of problems faced by management, providers, nurses, and staff during daily operations, not only from a space perspective but also from the other perspectives of flow as noted earlier. Due to the fact that many practitioners were not able to go through the interview process, questionnaires were provided to be completed at their convenience. The observation process included patient and provider shadowing, where redundant activities and motions were identified, and necessary suggestions were developed through the application of Lean.

Lean Consideration

Issues contributing to the inefficient use of space in the macro-level simulation model developed for this study included: Inefficient use of space, unnecessary travel time to waiting area for staff and patients, poor layout, non-value-added activities, waiting, inefficient procedures, understaffed clinics, nurses' station too small for clinic traffic, and the need for more storage space.

From the interviews and observations, the non-value-added activities identified are listed below. Some of these issues were thought to define appropriate performance measures for the simulation model.

- Inefficient use of space (nurses' station overcrowded; clerk desk layout does not provide human factor considerations; only one room is provided for provider)
- Unnecessary walking of staff and patients back and forth to the waiting area

- Poor layout (quantitatively verified by the simulation model)
- Two times waiting for patient (one for nurse and the other for provider)
- Inefficient procedures (no signage to guide patients into the appropriate space, minimum balance between waiting area and patient demand)
- Lack of equipment (only one printer for the entire team, separate printer is needed for printing letters and envelopes for clerical staff, need a counseling desk facing the patients)
- Clerks reach over the nurses to place charts in the cabinets while nurses are on the phone or computer
- Privacy issues as nurses need more privacy while on the phone
- Access issues as patients walk into the clinic and grab doctors and nurses
- More storage space is needed behind desks (maybe consider overhead storage)
- Disorganized chart holders

Field Observations and Data Collection

As part of the data-collection procedures, interview tools, questionnaires and observational methods were applied and are discussed below. Data collection included acquiring data from the clinic database and time studies, which included manual collection of time for each activity. The data collected served as input parameters for the simulation model. Data collected through the databases and time studies provided the information needed for utilization of clinical space and individual rooms. Figure 1 shows the patient distribution calculated from the data analysis of one year data.

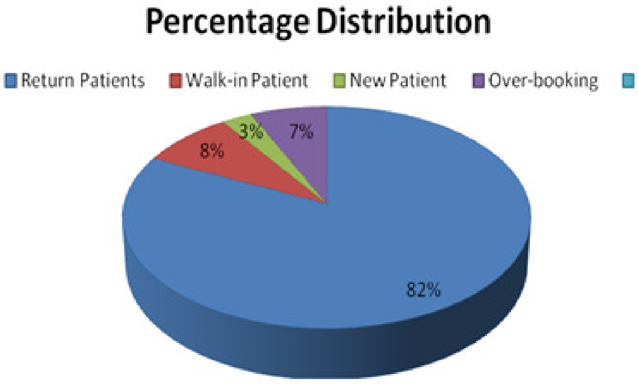


Figure 1. Percentage Distribution of Patients

A series of face-to-face interviews conducted with various staff in the clinic led to some key findings about the operation of the system. Interviews provided valuable insight about individual staff processing the patients and problems they face in a given day. The interview process took an average of 25 minutes per session. In some cases, follow-up interviews were necessary in order to validate the information. The interviews focused on daily job functions and the system's inefficiencies. Data collected were verified with the interview results to measure reliability.

Questionnaires were sent to staff who were unavailable for direct interviews and to collect data that could not be captured from the data bases. Questionnaires included checking whether all of the staff classifications are following the same operating procedures and whether there are differences between them which are difficult to capture from face-to-face interviews due to time constraints.

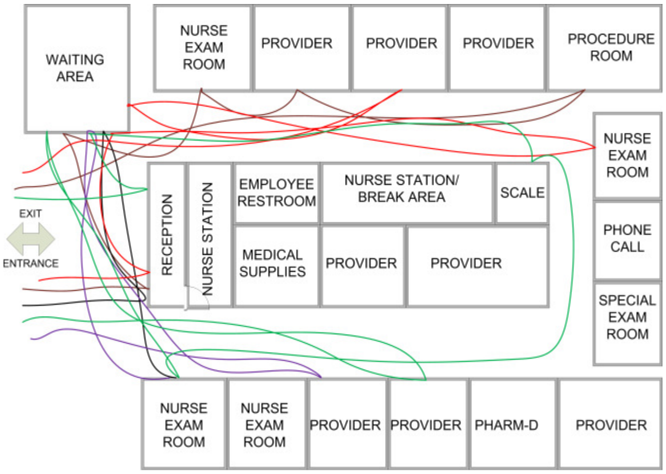


Figure 2. Spaghetti Diagram for Patient Flow

The observation process consisted of tracking patient flow from the moment they check-in at the clinic until they leave the system. This observation process enabled the authors to get an insight into the standard operating procedure and to draw process maps based on the spaghetti diagram shown in Figure 2. Figure 3 indicates the partial process map for the clinic under study.

The data-collection process started at the early stages of the simulation. Based on observations and completed interviews/questionnaires with staff, a comprehensive understanding of the operations and functions within the clinic was obtained. Based on knowledge of the current operating procedures and feedback from the Delphi study with clinic management and staff, a conceptual model was developed which eventually was used to develop a conceptual model

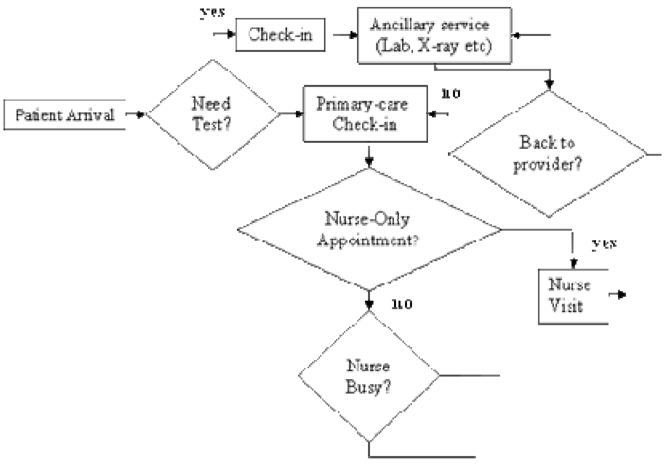


Figure 3. Snapshot of Patient Flow in a Typical Clinic Setup

required for building the simulation model, as shown in Figure 4.

Simulation Model

The simulation model considered utilization of providers, nurses and clerks. Providers were considered the primary resource utilizing the space in the simulation model. The utilization of nurses as a secondary resource was considered to be another important feature of the model. Nurses provide triage and assessment services to patients, which include taking vitals, doing clinical reminder tests, reviewing medications, etc. After the nurse assessment is complete, the patient is seen by the provider. Nurses typically work eight hours per day. Table 1 shows the input parameters and assumptions for one of the scenarios. The

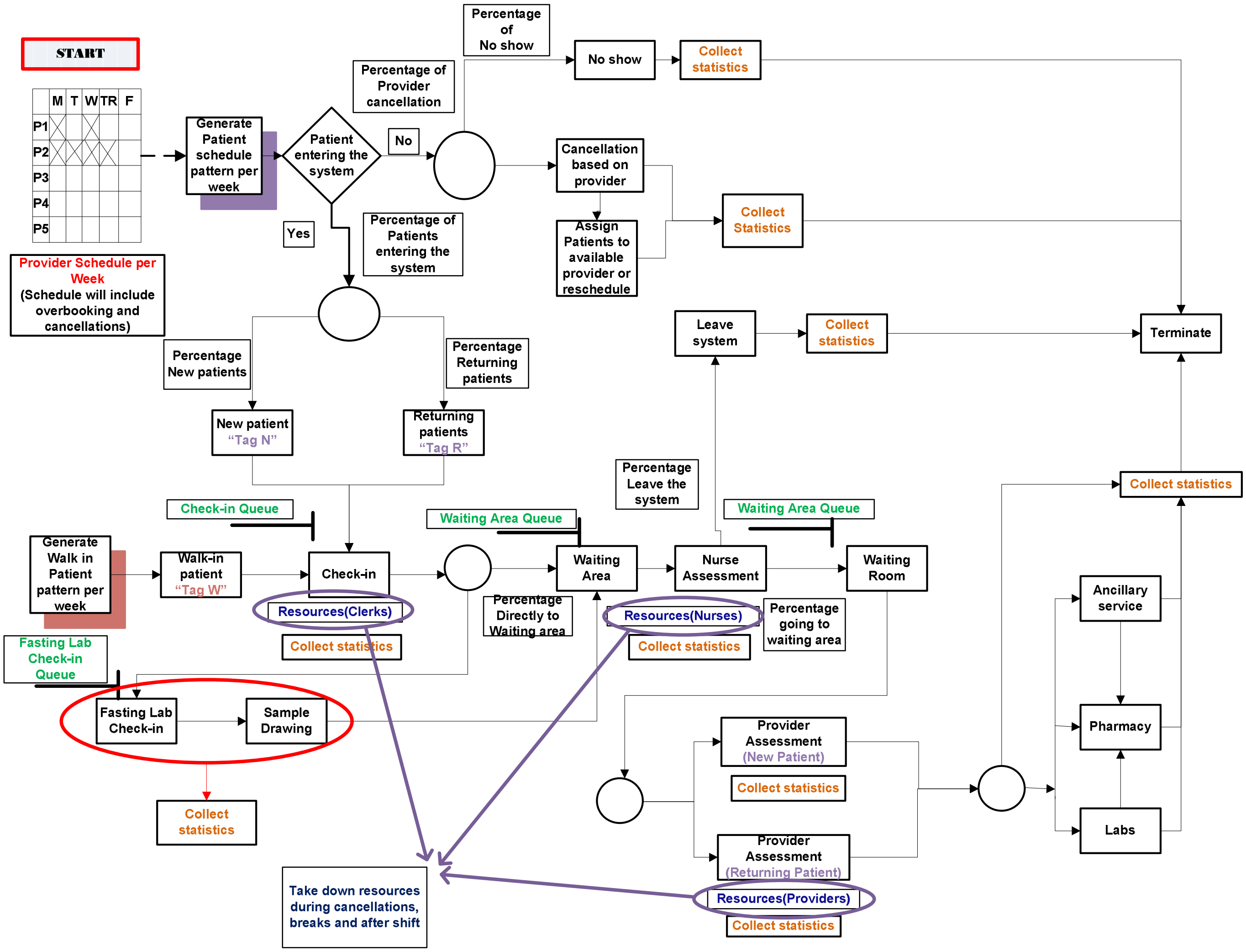
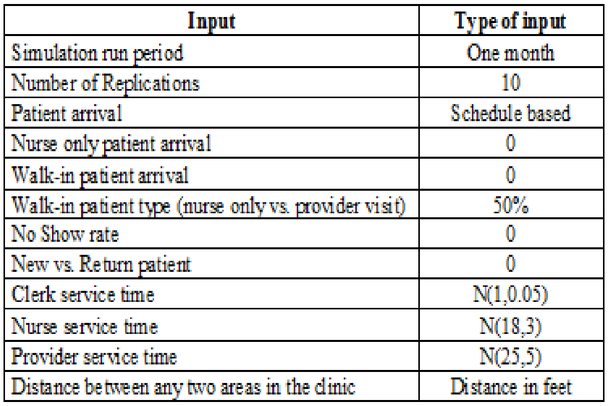


Figure 4. Snapshot of the Conceptual Model for the Clinic

utilization of clerks is also considered as an integral part of service provided to the patients. The clerks are mainly involved in patient check-in, verification and scheduling activities. Clerks typically work an eight-hour shift. A simulation model was built to examine impacts of various activities within the clinic and to provide an efficient environment within the clinical space for both patients and staffs. This model will also help to maximize the utilization of space and other resources; a simulation model was built to examine the impacts of various activities within the clinic. The performance measures considered for development of the model were maximize throughput, minimize wait time, minimize flow (transportation), and maximize utilization of nurses and providers. Figure 5 shows the partial simulation model developed in Arena.

Table 1. Input Parameters and Assumptions



Input	Type of input
Simulation run period	One month
Number of Replications	10
Patient arrival	Schedule based
Nurse only patient arrival	0
Walk-in patient arrival	0
Walk-in patient type (nurse only vs. provider visit)	50%
No Show rate	0
New vs. Return patient	0
Clerk service time	N(1,0.05)
Nurse service time	N(18,3)
Provider service time	N(25,5)
Distance between any two areas in the clinic	Distance in feet

Simulation Results

The simulation was analyzed considering the following resources: resource utilization, scheduling and distance traveled within the clinic. Four different scenarios were run to study these resources.

Resource Utilization

Utilization of resources focuses on the servers, receptionist, nurse and providers. One scenario was to add and remove assistants (nurse and/or receptionist) during busy and empty schedules. Another scenario was to change the providers' working time; in general, all providers start their work at the same time (8:30am and 1:30pm). This causes a heavy load for the nurses. By staggering the slots of the providers and nurses, this variation was expected to be controllable. This can be applied for all working days or only busy days.

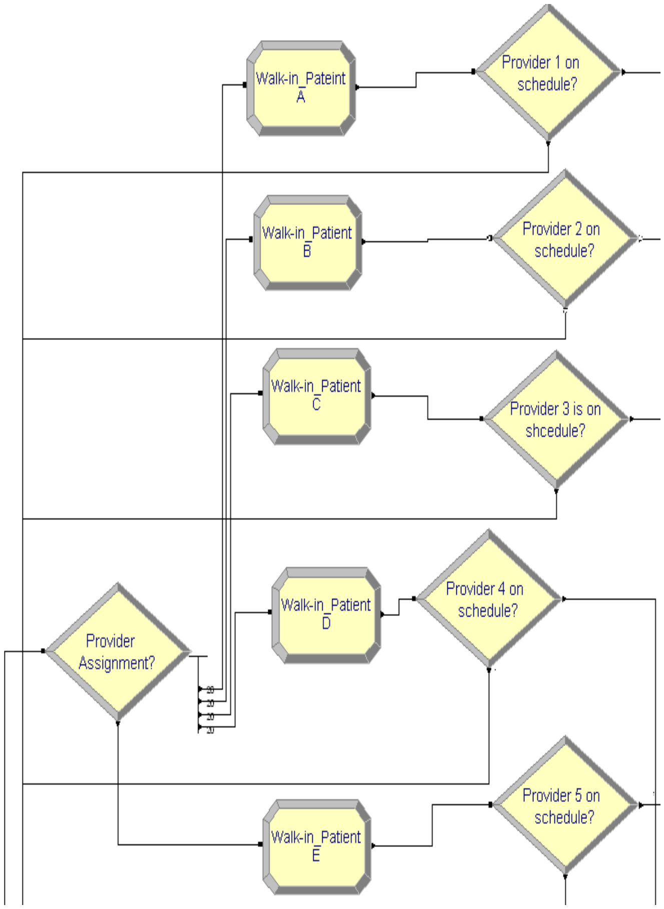


Figure 5. Snapshot of the Model in ARENA Version 12

Structured Scheduling

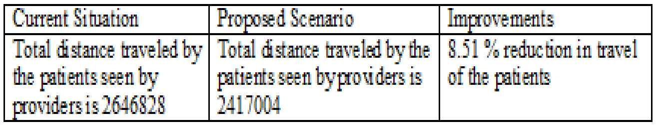
The scenario for this measure was to improve the system through patient type. What happens if patients are scheduled based on their type? For example, regular patients are visited in the morning while patients requiring long visits are scheduled in the afternoon; or, a scheduling pattern such as two regular patients following one long-visit patient could be defined.

Traveling in the System

It was important to determine the distances between any two areas in the system and approximate the daily traveling distance/time/cost in the clinic. It was also possible to figure out heavy traffic areas in the clinic. Based on that, a number of scenarios were tested and the best was selected. Scenarios included movement of resources and equipment and/or adding new resources and equipment. A summary of these scenarios is illustrated as follows:

Scenario 1: Changing the provider's workstation

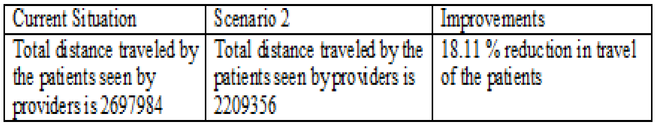
From the results, when the scenario was compared to the current situation it could be concluded that by moving the exam room of the busiest provider, (i.e. having their exam room closer to the waiting area) one can achieve a considerable reduction (8.5%) in the yearly distance (feet) traveled from the patient's perspective.



Current Situation	Proposed Scenario	Improvements
Total distance traveled by the patients seen by providers is 2646828	Total distance traveled by the patients seen by providers is 2417004	8.51 % reduction in travel of the patients

Scenario 2: Changing location of nurses and providers

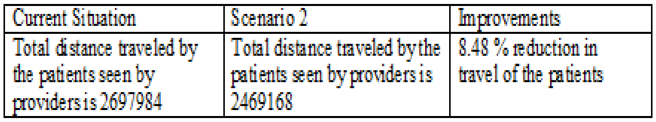
The analysis for this scenario, when compared with the current scenario, resulted in a reduction of 18% for the total distance (feet) traveled by the patients in one year.



Current Situation	Scenario 2	Improvements
Total distance traveled by the patients seen by providers is 2697984	Total distance traveled by the patients seen by providers is 2209356	18.11 % reduction in travel of the patients

Scenario 3: Assigning one nurse to each provider

This scenario, when compared with the current scenario, showed an 8.48% reduction in the total distance (feet) traveled by the patients in one year.



Current Situation	Scenario 2	Improvements
Total distance traveled by the patients seen by providers is 2697984	Total distance traveled by the patients seen by providers is 2469168	8.48 % reduction in travel of the patients

Scenario 4: Reducing staff travel/walking by improvising communication

The manual flow of information takes place between check-in clerks and nurses. For this, the check-in clerk prints documents related to the scheduled patient and places them in the nurse's document stack. If this flow of information could be done electronically, then the nurses need not come every time to the nurses' station to check for the patient information. The electronic information flow to the nurses can also be accompanied by some notification system such as color or light signals to indicate the arrival of a patient. A maximum of 3,000,000 feet of walking would be eliminated if this scenario were adopted.

Recommendations

From the study, the authors determined strategies to increase patient throughput and optimize clinic space utilization by changing flow and scheduling practices leading to an increased number of patients seen and a reduction in overall patient wait time. Such recommendations include quality improvement activities, continuous improvement interventions, redesigning inefficient processes, Lean tools, development of process maps, and standardization of process. Such recommendations are listed as follows:

1. Based on the interviews conducted with staff and management, the issues that lead to the inefficient process with respect to space were outlined and some of these issues were incorporated into the macro-level simulation model developed in this study. Simulation could be used as a tool to examine first-hand what impact any change would have on the system.
2. Minimizing no-show rates can be accomplished by scheduling and reminder strategies in advance. If successful, the utilization of the staff could decrease by around 10%.
3. Implement the use of Lean tools including 5S, VSM and Kanban cards.
4. Train staff on Lean techniques.
5. Standardize the process.
6. Develop cross-functional teams for continuous improvement implementation.
7. A systematic approach by which performance measures can be quantitatively measured on a regular basis needs to be developed. The performance measures identified in this study were resource utilization, patient waiting time and cycle time, traveling in system (patient and staff), patient accessibility and throughput.

Conclusions and Future Work

Lean implementation in a clinical setting focuses on increasing the throughput in the system, reducing patient waiting times, and increasing utilization of resources by reducing idle time of staff. This optimization of clinic space is classified based on the flow, layout and application of Lean tools. From the study conducted here, the strategy was to increase patient throughput by changing scheduling practices, thereby increasing the number of patients seen and reducing overall patient wait time. Additional recommendations for future study include:

1. Splitting the current simulation model (which considers clinic flow and space utilization in the same model) into two separate models; one to consider the flow patterns and the other to focus on the space utilization aspect. As such, the first model can analyze the flow more efficiently and the output of such a model can be plugged into the second part.

2. Customize the simulation model for Lean interventions. It is possible to observe the impacts of Lean intervention before they are implemented. Once the manager determines what intervention will be implemented, a customized simulation model could be developed.
3. Implement a digitized data-collection system which can be used for simulation of data. Inaccurate data result in sub-optimal analyses.
4. Add more advanced features to the developed model to make it user friendly. Users can easily run the model from a friendly environment such as Excel.
5. Expand the scope of the model by considering the impact of other clinics which have interaction with primary care clinics such as lab, specialty and pharmacy.
6. Customize the simulation model for Lean interventions. It is possible to observe the impacts of Lean intervention before they are implemented. Once the manager determines what intervention will be implemented, a corresponding simulation model can be developed. However, to do that the current model should be customized case by case.

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NATURAL ORGANIC FIBER MESHES AS REINFORCEMENTS IN CEMENT-MORTAR MATRIX

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Abstract

The use of fibers as reinforcing materials in cement-based composites has been widely explored. The challenge facing mankind today is focused on how to utilize natural organic fibers available locally in producing materials that would be appropriate for many low-cost construction project, especially in developing countries. This study is aimed at investigating the possibility of using cellulose fibers—namely, abaca and sisal—as oriented reinforcements in the form of meshes in cement-mortar matrices for the improvement of the overall performance of the composites. Rice Husk Ash (RHA) is also used as a replacement of part of the Ordinary Portland Cement (OPC) to reduce the decomposition of abaca and sisal fibers due to the alkaline environment of the cement matrix. Significant improvements in the overall performance of the cement-based composites were observed.

Introduction

The use of fibers to reinforce brittle materials can be traced to biblical times when straws were used in brick manufacture [1]. Fiber-reinforced cements and concretes are today firmly established as construction materials. Since the early 1960s, extensive research and development have been carried out with fiber-reinforced composite materials leading to a wide range of practical applications. Considerable research has gone on in the field of fiber-reinforced, cement -based materials, and there is now an abundance of literature on the subject. Fibers such as sisal and coconut fibers used as reinforcement in the form of short fibers in cement matrices were explored [1]. Other natural fibers like coir, jute and hibiscus cannebinus in cement-mortar slabs were also investigated and results obtained show that the addition of these fibers increased the impact resistance of the plain mortar slab [2].

The major advantage of fiber reinforcement is to impart additional energy-absorbing capability and to transform a brittle material into a pseudo ductile material. Fibers in cement or in concrete serve as crack arrestors, which can create a stage of slow crack propagation and gradual failure [3]. Application of natural fibers to replace asbestos because of their availability in the tropical and subtropical parts of the world has been explored. Performance of mortar roofing tiles reinforced with natural fibers was studied [4]. Sisal fiber was used as reinforcement in cement-based composites and has shown that the composites are reliable materials to be used for structural materials. It has also been found that this material could be a substitute for an asbestos-cement composite [5]. Another study was done to analyze mechanical, physical and thermal performance of roofing tiles produced from cement-based matrices reinforced with sisal and eucalyptus fibers [6]. The study found that vegetable fibers are acceptable as substitutes for asbestos as reinforcements in cement-based sheets.

Replacement of asbestos fibers is seen as an area of priority research, particularly in developing countries where, apart from health problems, low-cost materials are urgently needed. Natural cellulose fibers have been produced either as a full or partial substitute for asbestos because they have similar characteristics such as high aspect ratio, high tensile strength, toughness, flexibility and, above all, buoyancy of the fiber in the cement [7]. Some developing countries, such as India, China and Russia have continued widespread use of asbestos. The most common is corrugated asbestos-cement sheets or "A/C Sheets" for roofing and for side walls [8]. Cellulose fiber-reinforced cement can provide the highest performance-to-cost ratio among fibrous cement composites for the replacement of asbestos. Past studies have shown that the reinforcement action of cellulose fibers in cementitious matrices is quite good relative to other fibers such as glass.

Cement-based materials suffer from one common shortcoming; they fail in a brittle manner under tensile stresses or impact loads or lack resistance to the propagation of cracks. The use of short, randomly distributed fibers is an effective method of strengthening brittle materials against cracking under stress. Broadly, the reason why weak, brittle materials are made tougher by very small additions of fibers is that cracks are deflected in the presence of fibers and, as a consequence, the toughness or ductility is dramatically increased. Fibers also give the cement composite material a very good plasticity in its fresh state after mixing the cement with water, making it possible to cast the material into different varying forms such as roofing sheets, floor tiles, etc. Realizing that short fibers offer effective reinforcing characteristics at improving the cement-based materials' properties, it is therefore essential to investigate whether reinforcing the cement-based materials with long-oriented fibers in the form of fiber meshes will give improved properties to the composites.

The most commonly used fibers are steel, glass, carbon and graphite, which contribute high strength and modulus for structural applications. However, these fibers are relatively expensive (which is critically important in third-world countries) compared to natural fibers. These conditions have resulted in a proliferation of exploratory studies on the use of natural fibers as reinforcement in fiber-reinforced composites. Cellulose fibers appear to be the most promising material because they are inexpensive and abundantly available in most of the developing countries.

Fiber Reinforcement

Two types of fibers—abaca and sisal—locally obtained from the Philippines and Thailand, respectively, were used as reinforcing materials in making fiber-reinforced cement-mortar composites. The main variables in the study were fiber type and fiber content. The fibers used as reinforcements were in the form of meshes. The fiber content was represented by the number of mesh layers and varied in three different cases. The composites being investigated were of an OPC-RHA-sand matrix reinforced with fiber meshes. RHA was added to improve the durability of natural fiber-reinforced mortar [9].

The scientific study of natural fiber reinforcement has followed the developments with synthetic fibers. The reasons for putting fibers into cement-based materials are generally agreed to be as follows [10]:

- Improvement of flexure (bending strength)
- Improvement of impact toughness
- Control of cracking and change in failure behavior to give post-crack load-bearing capacity, and
- Change in the flow characteristics of the fresh material

Abaca

Abaca, the common name for *Musa textilis*, is a species of banana native to the Philippines, grown widely as well in Borneo and Sumatra. Abaca fiber, unlike most other leaf fibers, is obtained from the plant leaf stalks (petioles). Although sometimes called Manila hemp, Cebu hemp or Davao hemp, it is not related to true hemp. Abaca fiber, known worldwide as Manila hemp, is obtained from the leaf sheath of the abaca plant. Abaca is indigenous to the Philippines and is similar to banana in appearance except that the leaves are upright, pointed, narrower and taper more than banana leaves. Abaca fiber is considered the strongest of the natural fibers. The length of the fiber varies from three to nine feet or more, depending on the height of the plant and the age of the leaf sheath. The color of the fiber ranges from ivory white to light and dark brown.

Abaca fiber, valued for its strength, flexibility, buoyancy, and resistance to damage in saltwater, is chiefly employed for ships' hawsers and cables, fishing lines, hoisting and power-transmission ropes, well-drilling cables and fishing nets. Some abaca is used in carpets, tables and fabrics mainly used locally for garments, hats and shoes.

Figure 1. Abaca Plant and Abaca Fibers

Sisal

Sisal, the common name for *Agave sisalana*, is a plant of the agave family Agavaceae that yields a stiff fiber traditionally used in making twine, rope and dartboards. The term may refer either to the plant or the fiber, depending on context. It is sometimes incorrectly referred to as sisal hemp because hemp was for centuries a major source for fiber, so other fibers were sometimes named after it.

The plant's origin is uncertain; while traditionally it was deemed to be a native of Yucatan, there are no records of botanical collections from there. H.S. Gentry hypothesized a Chiapas origin, on the strength of traditional local usage [11]. In the 19th century, sisal cultivation spread to Florida, the Caribbean islands and Brazil, as well as to countries in Africa—notably Tanzania and Kenya—and Asia. The first commercial plantings in Brazil were made in the late 1930s and the first sisal fiber exports from there were made in 1948. It was not until the 1960s that Brazilian production accelerated and the first of many spinning mills was established. Today, Brazil is the world's leading producer of sisal [11]. There are both positive and negative environmental impacts from sisal growing.

Sisal fiber is valued for cordage use because of its strength, durability, ability to stretch, affinity for certain dyestuffs and resistance to deterioration in salt water. Sisal ropes and twines are widely employed for marine, agricultural, shipping and general industrial use. The fiber is also made into matting, rugs, millinery and brushes.

Figure 2. Sisal Plant and Sisal Fibers

Experimental Investigation

The constituent materials used in this study were:

- Ordinary Portland Cement (OPC) Type I
- Rice Husk Ash (RHA) obtained by burning rice husk using the machine developed by We [12], and was used as a partial replacement of OPC
- Ordinary tap water
- Natural river sand passing ASTM sieve no. 50 and retained on sieve no. 100
- Rheobuild 1000 Superplasticizer
- Abaca and sisal fibers

The abaca and sisal fiber meshes were fabricated manually by using weaving frames especially designed for this study. Formworks for the composite plate samples were also especially designed. The casting of the test specimens was conducted manually using the specially designed molds. Abaca and sisal fiber composite plates were fabricated separately in three different variations of fiber contents (i.e., 2-, 4- and 6-layer fiber meshes). Control specimens with no fiber reinforcement were also fabricated for comparative purposes. For the investigation of the properties of fiber-mortar composite plates, 300 x 300 x 10mm plates were fabricated using the designed molds. After 28 days of curing in a humid room, the specimens were cut into 250 x 100 x 10mm plates. The plates were then allowed to dry for one day and then tested according to ASTM C78 / C78M [13]. Details of the testing program are shown in Table 1.

Table 1. Testing Program of the Properties of Fiber-Mortar Composite Plates

Type of Plate	Fiber Content (Number of Fiber Mesh	Plate Dimension	Type of Test	Number of Specimens
No Fiber (control)	0	A	M	3
		A	W	3
		B	F	3
Abaca Fiber -Reinforced	2	A	M	3
		A	W	3
		B	F	3
	4	A	M	3
		A	W	3
		B	F	3
	6	A	M	3
		A	W	3
		B	F	3
Sisal Fiber-Reinforced	2	A	M	3
		A	W	3
		B	F	3
	4	A	M	3
		A	W	3
		B	F	3
	6	A	M	3
		A	W	3
		B	F	3

A = 50 x 50 x 10mm, B = 250 x 250 x 10mm, M = Moisture Content, W = Water Absorption, F = Flexural Strength

The properties of the fiber-mortar composite plates were experimentally investigated. The main variables were the fiber type and the fiber content expressed in terms of the number of fiber mesh layers. The fiber contents used in the fabrication of the fiber-mortar composite plates were 2-, 4- and 6-layer fiber meshes. From the production of the fiber meshes for reinforcements to the fabrication of the fiber-mortar composites, care was taken to ensure proper and accurate shapes and dimensions of the composites to be used as test specimens. All test specimens were cured under the same environmental conditions for 28 days before testing so as to have more reliable results. Tests were performed to determine the flexural strengths expressed in terms of modulus of rupture of the composite plates. Other relevant properties obtained from these tests were the modulus of resilience and modulus of toughness of the plates.

Moisture Content

The moisture content of the plates was conducted using the 50 x 50 x 10mm specimens. The specimens were weighed before being placed in the oven at a temperature of 105^{o}C for 24 hours. The weights of the oven-dried specimens were recorded after cooling at room temperature. The ratio of the difference between natural and oven-dried weights to the oven-dried weight expressed as a percent is the moisture content of the plate.

Water Absorption

The water absorption of the plates was measured using the 50 x 50 x 10mm specimens. The specimens were immersed horizontally in water for 24 hours. After the 24-hour immersion, the specimens were taken out and allowed to drain for 10 minutes. Subsequently, the excessive water was wiped off with an absorbent cloth so as to achieve a saturated surface-dried condition after which the specimens' weights were measured and recorded. The specimens were then kept in the oven at a temperature of 105^{o}C for 24 hours. The specimens from the oven were then cooled at room temperature and then the weights were taken and recorded. The water absorption of the plate is the ratio of the difference in weight between the saturated surface-dried weight and the oven-dried weight to the oven-dried weight expressed as a percent.

Flexural Strength

The 250 x 100 x 10mm specimens were used to measure the flexural strength of the plates. The specimen was supported over a span of 225mm and subjected to third-point loads until failure. The flexural strength was expressed in terms of modulus of rupture. Other relevant properties determined from the flexural strengths were the modulus of resilience and modulus of toughness. American Concrete Institute (ACI) [14] defines modulus of rupture as a measure of the ultimate load-carrying capacity of a material. ACI defines toughness as the capacity of a material to absorb energy during the application of load to fracture. It is said to be dependent on both strength and ductility. The modulus of toughness is expressed in terms of the work performed in deforming a material to fracture.

Test Results

Moisture Content and Water Absorption

The moisture content and water absorption of the plain mortar plates were increased with the addition of abaca and sisal fibers, as shown in Tables 2 and 3, respectively. It was found that the moisture content and water absorption of the abaca and sisal fiber-mortar composite plates were directly proportional to the fiber content. As to the type of reinforcement, it was found that the composites with abaca fibers showed higher moisture content and water absorption than those containing sisal fibers in all cases.

Table 2. Average Moisture Content of Plates

Type of Fiber Reinforcement	Moisture Content (%) , at Number of Fiber Mesh Layers			
	0 layer (control)	2 layers	4 layers	6 layers
Abaca		6.44	6.92	7.66
	6.06			
Sisal		6.32	6.80	7.50

Table 3. Average Water Absorption of Plates

Type of Fiber Reinforcement	Water Absorption (%) , at Number of Fiber Mesh			
	0 layer (control)	2 layers	4 layers	6 layers
Abaca		8.72	8.90	9.24
	7.74			
Sisal		8.51	8.75	9.15

Modulus of Rupture

There were marked improvements in the moduli of rupture of the plain mortar plates in the presence of abaca and sisal fibers; abaca being more effective than sisal. The plates reinforced with 2-, 4- and 6-layer abaca fiber meshes were observed to produce moduli of rupture about 60%, 72% and 85%, respectively, higher than that of the plain mortar plates. On the other hand, the plates reinforced with 2-, 4- and 6-layer sisal fiber meshes were observed to produce moduli of rupture about 54%, 65% and 74%, respectively, higher than that of the plain mortar plates. The average moduli of rupture of the plates obtained from the tests are shown in Table 4. It can be seen from the test data that for all cases, the moduli of rupture increased with the increase in fiber content.

Table 4. Average Modulus of Rupture of Plates

Type of Fiber Reinforcement	Modulus of Rupture (MPa) , at Number of Fiber			
	0 layer (control)	2 layers	4 layers	6 layers
Abaca		8.625	9.300	9.975
	5.400			
Sisal		8.325	8.925	9.375

Modulus of Resilience

The amount of energy recovered per unit volume of a material when it is stressed to its elastic limit and then the stress is relieved, is the elastic resilience of the material. Table 5 shows the average moduli of resilience of the fiber-mortar composite plates. The increases in the moduli of resilience of the plain mortar plates were about 68%, 64% and 50% with the addition of 2-, 4- and 6-layer abaca fiber meshes, respectively. In the case of 2-, 4- and 6-layer sisal fiber meshes, the increases in the moduli of resilience of the plain mortar plates were about 59%, 55% and 45%, respectively. From the test results, it was observed that the moduli of resilience of the fiber-reinforced plates decreased as the fiber contents increased. It was also evident from the results that the abaca fiber-mortar composites have higher moduli of resilience than the sisal fiber-mortar composites.

Table 5. Average Modulus of Resilience of Plates

Type of Fiber Reinforce-ment	Modulus of Resilience (N-m) , at Number of Fiber			
	0 layer (control)	2 layers	4 layers	6 layers
Abaca		0.037	0.036	0.033
	0.022			
Sisal		0.035	0.034	0.032

Modulus of Toughness

The average moduli of toughness of the fiber-mortar composite plates are shown in Table 6. Results show significant increases in the moduli of toughness of the plain mortar plates and were obtained with the addition of abaca and sisal fibers. The fiber-mortar composite plates containing 2-, 4- and 6-layer abaca fiber meshes have shown increases in the moduli of toughness of 263%, 339% and 400%, respectively. Likewise, composites containing 2-, 4- and 6-layer sisal fiber meshes have shown increases in the moduli of toughness of 235%, 288% and 353%, respectively. Results have shown that the moduli of toughness were significantly improved with the increase in fiber content. This is a demonstration of high ductility imparted by low modulus fibers like abaca and sisal fibers. It has also been found that composites with abaca fiber reinforcements have higher moduli of toughness than those with sisal fiber reinforcement.

Table 6. Average Modulus of Toughness of Plates

Type of Fiber Reinforce-ment	Modulus of Toughness (N-m) , at Number of Fiber			
	0 layer (control)	2 layers	4 layers	6 layers
Abaca		0.178	0.215	0.245
	0.049			
Sisal		0.164	0.190	0.222

Conclusion

An experimental study was conducted to assess the properties of natural cellulose fibers—namely, abaca and sisal—and cement-mortar composites reinforced with these fibers. The study looked into the effects of fiber addition in the form of meshes on the performance of these natural fiber-reinforced cement-mortar composites.

The moduli of rupture of the plain mortar plates increased by about 54% – 85% with the addition of abaca and sisal fibers. The increases in the moduli of resilience of the plain mortar plates with the addition of abaca and sisal fibers were about 45% – 68%. The moduli of toughness of the plain mortar plates were significantly improved (about 235% – 400%) with the addition of abaca and sisal fibers. For all cases, plate properties were increased more with the addition of abaca fibers than with sisal fibers. The values of the moduli of rupture and moduli of toughness increased with the increase in fiber content, while the values of the moduli of resilience decreased with the increase of fiber content.

This study found that the use of natural organic fiber meshes as reinforcements in cement-mortar matrices considerably improved the overall performance of the plain mortar plates. Hence, such fiber reinforcements possess very good potential for use as reinforcements in cement-based materials.

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TEST-BED DEVELOPMENT OF SHARED-MISSION AUTONOMOUS GROUND/AERIAL DISSIMILAR SWARMING

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Abstract

Many researchers are currently focused on teams of near identical robots [1], referred to as swarming or swarm robotics. This research area is based on the observance of swarms of insects that complete a significantly larger mission than any single insect could hope to accomplish alone. For example, the mounds built by ants, a beehive or a hornet's nest. However, to most people all bees look the same, but from the bee's perspective, and the perspective of an entomologist, each bee hive is home to many different types of bees all with a job they are particularly suited for and assigned to. To truly mimic the swarming of insects, the robots in swarm robotics should be designed to complement each other and not necessarily be identical. To this end, this study aimed to build up robots that are meant to work together on a shared mission, but that are far from identical. The mission was to base the design of the robots around discreet aerial surveillance and target identification with the ability to transport heavy loads and heavy artillery, a mission necessary to many military actions. To complete this study and test the developed strategies in the real world, the group developed a teamed system concept as a test bed. The system includes a robotic aerial quadrotor helicopter and a robotic ground vehicle with a weapon. The mission under design was to allow the helicopter to identify the target and have the ground vehicle navigate to GPS coordinates identified by the helicopter, confirm the identification with its own vision system and "destroy" the target. For safety purposes, the weapon was a paintball marker. This paper will discuss the test bed in its current stage, identify hurdles to success, and directions for future research.

Introduction

Robotic swarming is a coordination approach to an autonomous mission that involves the use of multiple robots to work together to accomplish a single goal. It is characterized by a collective behavior from the interactions of the robots with each other as well as their environment. The robots are often simple in design and functionality, but through their multitudes they obtain greater ability. The main focuses in swarming have been the physical characteristics of the robot and the controlling behaviors implemented as control algorithms.

Swarming has often been studied by observing the swarm intelligence that is inherent to insects in nature. These studies often show that by creating simple individual rules inherent to each robot, you can create complex behaviors within a swarm of robots. Each individual robot must constantly communicate and alter its behavior in order to react appropriately within a group. Often, in order to achieve a larger swarm, the individual robot must be simple so that it uses as few resources as possible. This can often force the focus of the accomplishment of the goal on the swarm level and not on the individual.

The many current applications of swarming technologies are categorized by the functionality and the control methods inherent to the individual robot. Each function will determine the application, but swarming can take one function of the individual and create a new function as a whole. Control methods that have been used in the swarms hinge upon physical limitations and technological ability.

Currently, several teams of researchers are working to create some form of a swarm of robots to complete a mission. A team at the University of Southern California is working towards a bio-mimicry approach to the control of each member of the swarm by using what they call the Digital Hormone Method (DHM) [2]. Meanwhile, their counterparts at the University of Karlsruhe in Germany seem less interested in mirroring the biology seen on earth as they are preparing a large team of centimeter-scale robots to explore and colonize mars. While this team isn't using a bio-inspired control method, they are taking advantage of a concept seen in nature that when one in the swarm is disabled the swarm itself continues [3]. Yet another team, at the University of Essex in the United Kingdom, is working on a "flock" of quadrotor helicopters that they call Owls. Like the German group, the team in the UK considers the robustness of the swarm to be of utmost importance. That is, when one or even a few robots are disabled, the swarm can continue with the mission. However, this group has taken the swarm a step further such that each member of the group shares its data and processing power with the others in order to not only work together but to think together as well [4].

While these three groups represent only a part of what is going on in the world when it comes to robotic swarming technologies, it gives a brief picture of the current focus in this area of research. All of these teams seem to have one thing in common; their swarm members are identical or near identical. On the other hand, the authors of this current study are working on using a group of dissimilar robots together as a kind of swarm. Just as in a beehive, most of the bees may look the same to us but from an entomological viewpoint the drone bees and the worker bees are outfitted very differently for their associated tasks. This approach allows us to take a mission further and accomplish larger goals such as a military action or a disaster site where debris has collapsed and people are trapped under it. In these scenarios, one robot type could squeeze its way into tight spaces to locate the trapped people or the hiding targets of a military action. Another, different robot can be designed to lift rubble to uncover the victims or engage the military target. If there was a swarm of locator robots and no robots design to actuate, then it is likely that they would be unable to complete the mission alone. Attempts at making a team of similar, miniature robots with the capability to combine into something more capable is the only other alternative, but this option is likely more difficult.

This kind of tandem work approach with all types focused on one goal has excellent military applications. The test bed in this study is of a military operation consisting of seeking visually identifiable targets and destroying them. Using the mentality of multiple, identical member swarms working as a “Great Swarm”, one can employ not only robots capable of target identification and others capable of payload delivery, but one can have robots that collect specific intelligence, others that clear away impeding objects in the path, and still others that recover and repair their wounded counterparts. Each of the robots would be designed for just one specific function that would facilitate making a robot that is cheaper and smaller instead of many robots capable of doing everything themselves. This Great Swarm benefits from the uniqueness of each member swarm as well as the robustness of the individual swarm.

Mission and Test Bed

In order to accomplish the design of a robot team, a specific mission is needed. To this end, the team has designed the following mission and member identification as a target for the system design. To design and construct a Vertical Take Off and Landing (VTOL) Quadrotor Helicopter (helicopter) and Autonomous Mobile Sentry Gun (sentry) such that the helicopter is capable of vertical take-off from the top surface of the sentry after human-specified GPS coordinates have been reached by the team. Furthermore, once the helicopter has lifted off it shall be tasked with locating a visually pre-defined target with the aid of its onboard vision system and then wirelessly relaying GPS coordinates back to the sentry. The sentry will then carry out target elimination through the use of a paintball marker after visual confirmation from its own onboard vision system. During and after the mission, the helicopter will be capable of landing back onto the sentry for battery recharging and theatre exit upon mission completion.

The Quadrotor Helicopter is an aerial vehicle that has recently come into interest in the robotic research community since battery technology has become inexpensive and light-weight enough to power small-scale aerial vehicles for relatively long periods of time between charges. Additionally, the popularity of hobby-level remote control aerial vehicles has allowed some researchers the ability to enter this arena, given the economies of scale for parts that can be shared with the remote-control community. From a research standpoint, the vehicle is highly desirable as a flight test bed mainly due to its inherent stability, given four points of thrust and its relative ability to carry a small payload. While some research focuses on the flight and aerodynamics of the Quadrotor Helicopter, most recent research has been focused on the use of the flying vehicle once airborne. Much of this research [5-7] has focused on using vision systems on board the vehicle to identify objects below and to control the flight pattern of the vehicle. Helicopters are desirable over other forms of aerial vehicles for some tasks, such as surveillance, due to the ability to hover in a specific location.

A sentry gun is most commonly known in the computer gaming community because it represents more science fiction than it does commonly used military equipment. A sentry is a device that automatically senses the presence of enemies, locates their position, and eliminates or disables them. Called the Phalanx CIWS, the first military use of a sentry was developed by Raytheon and first deployed in 1980 for the United States Navy. It uses an advanced radar system to locate and target potential enemies to protect a ship or fleet of ships from missiles or other weapons [8]. Another, more recent and on-going project taken on by the United States military is the Counter–Rocket, Artillery, Mortar (C-RAM) project. Since 1993, the C-RAM project has served the same function as the Phalanx CIWS system for land-based protection [9].

While these two projects represent significant research, funding and effort on the part of many constituents, the systems are not autonomously mobile. That is, they go were the ship does or are mounted on a stationary building and wait for an enemy presence. In some cases, it seems necessary to allow the sentry the ability to travel and seek out a target. This is the case, at least partially, in the ROBART program currently in its third phase of research [4]. The ROBART research program conducted by the SPAWAR Systems Center is currently operating under ROBART III and is capable of navigating a security pattern in confined spaces such as a warehouse. In this stage of development, the vehicle fires rubber bullets or simulated tranquilizer darts at its identified enemy [10].

Currently, researchers are considering systems such as the Phalanx, the C-RAM and ROBART III, but they seem focused on centralized sensing as opposed to remote or decentralized sensing, which would require robot teaming or swarming. Decentralized sensing gives the mobile sentry the ability to understand the environment outside of its sensing range through wireless communication with other, different robots; robots designed to be the eyes and ears of the sentry. At this time, it is not apparent that anyone is investigating the use of the Quadrotor Helicopter or any other aerial vehicle as a part of an autonomous robot team to complete shared missions with a mobile autonomous sentry or group of sentries.

The Mobile Sentry Design

The team has designed and built multiple sentry systems, the first being remote controlled to gain an overall picture of the issues presented by the platform. Shown in Figure 1 is the current mobile platform in process. Currently, the platform is mechanically complete and functional but awaiting electrical controls.

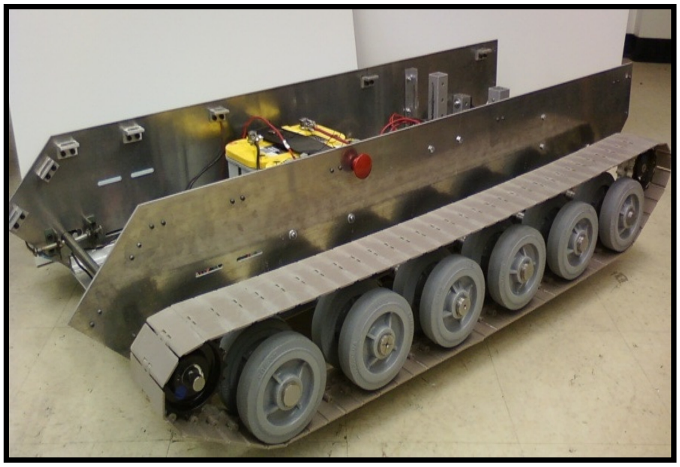


Figure 1. The current platform

The platform is ~1500mm long, powered by a 24V 55Ah lead-acid battery through two 4.5hp electric motors, and can attain a top speed of ~1.2m/s. As the design for the control system is preliminary and untested, it will not be presented in this paper. However, the control system for the turret apparatus that is to mount on the top of the above platform is in testing stages and will be presented below. Figure 2 shows the turret assembly in its bench testing phase, before it is mounted in the platform.

The weapon, a semiautomatic paintball marker, is mounted such that the center of rotation coincides with the center of gravity to minimize the motor torque required to move into and maintain a position. Because of the low level of torque required, the weapon's elevation control was designed around a standard ¼-inch-scale hobby servo motor. However, the turret rotation was too large to benefit from hobby level servo motors in an affordable range. Therefore, a custom servo system was developed for turret rotation. The system uses a standard DC motor and a shaft encoder for feedback. While they are mounted separately on a chain drive system, they are each mounted with a sprocket of the same size to provide a feedback ratio of 1:1. The turret rotation is controlled with a standard digital PID loop and tuned using the Integral Square Time Error (ISTE) method. Not shown in Figure 2 is another hobby level servo used for firing of the weapon. Figure 3 shows the implementation of the PID control. Of great importance to the research team is the fact that the entire system is controlled by an embedded system. This is the Propeller multi-core microcontroller from Parallax. This controller is an 80MHz microcontroller with eight cores and is available in a 40-pin DIP package, a 44-pin QFN package, and a 44-pin QFP package.

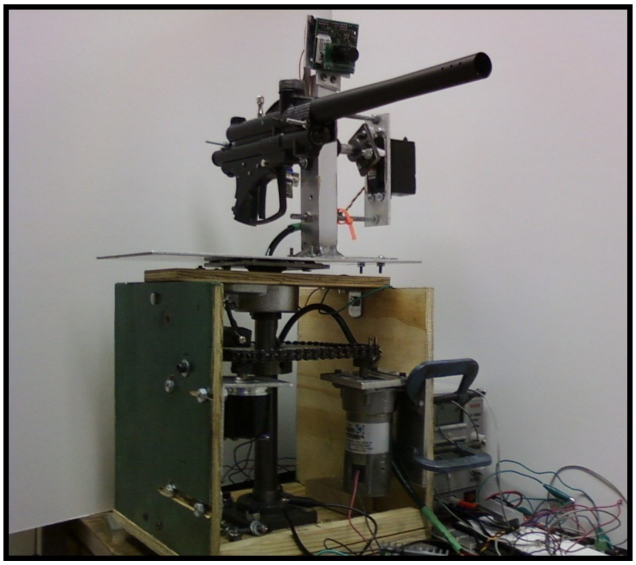
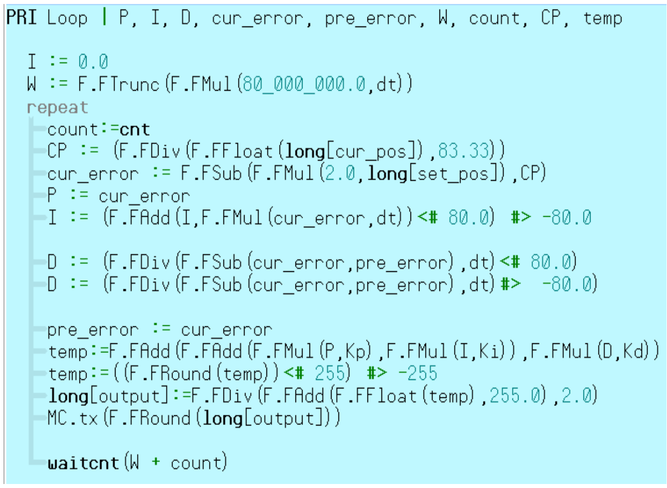


Figure 2. Mobile Sentry Firing System in Testing

The PID controller was implemented on a separate core of the microcontroller and uses tuned gain parameters of Kp = 27.486, Ki = 0.05, Kd = 0.309 and a 50ms integration time. The available encoder that was implemented on this project is a 60,000 pulse-per-revolution encoder, which is much more than necessary so that the implemented counts could be divided down to 720 pulses per revolution. This provides a system that can be tuned in coarser increments. Furthermore, the encoder is not an absolute encoder, so a home switch was installed that could be actuated by the system triggers on boot and before entering the PID control loop. This home position is located just outside of the normal operating range. For obvious reasons the switch trigger position is considered 0° while the operating range is 10° through 190° positioning the weapon a full 180°; 90° to the left and right of the forward position.

Because the weapon elevation is handled by a standard servo motor, the implementation is quite simple. A standard servo motor responds to a pulse sent out in 10-20ms cycles. The pulse width determines the motor position that is traveled to and held. The maximum and minimum weapon elevation angles are associated with pulse widths of 1.4ms and 1.8ms respectively. The range of the elevation is 45° above parallel and 15° below parallel.



```
PRI Loop | P, I, D, cur_error, pre_error, W, count, CP, temp

  I := 0.0
  W := F.FTrunc(F.FMul(80_000_000.0,dt))
  repeat
    count:=cnt
    CP := (F.FDiv(F.FFloat(long[cur_pos]),83.33))
    cur_error := F.FSub(F.FMul(2.0,long[set_pos]),CP)
    P := cur_error
    I := (F.FAdd(I,F.FMul(cur_error,dt))<# 80.0) #> -80.0

    D := (F.FDiv(F.FSub(cur_error,pre_error),dt)<# 80.0)
    D := (F.FDiv(F.FSub(cur_error,pre_error),dt)#>  -80.0)

    pre_error := cur_error
    temp:=F.FAdd(F.FAdd(F.FMul(P,Kp),F.FMul(I,Ki)),F.FMul(D,Kd))
    temp:=((F.FRound(temp))<# 255) #> -255
    long[output]:=F.FDiv(F.FAdd(F.FFloat(temp),255.0),2.0)
    MC.tx(F.FRound(long[output]))

    waitcnt(W + count)
```

Figure 3. PID Control Implementation

In Figure 3, the implementation of the PID loop is shown. The propeller microcontroller does not have built-in floating -point capabilities so it was constructed using an IEEE 754 technique. Therefore, when two numbers need to be multiplied together, the resulting code is F.FMul(A,B) as the floating point math is completed by an object file with the 'F.' identifier. Additionally, after the total controller effort has been calculated, the output (ranging from -255 to 255) must be shifted to range from 0 to 255. To the motor controller, 0 is full speed reverse and 255 is full speed forward, while 127 is stop. The motor controller is set up in serial communications mode so the MC.tx command simply transmits a byte of data representing the controller effort by another object file.

Once fully implemented, the results of the tuned PID rotation control are shown in Figure 4. One interesting note is the response overshoot and oscillation when the angle increase is greater than the angle decrease. This is due to the fact that the system is chain driven and the sprocket alignment is not perfect, given the bench-top test setup nature of the system. It was expected that once the system is mounted inside the mobile platform that the response from an increase will be closer to that of the response to a decrease. When it is remounted, the system will likely require retuning.

Of course, when the system is in operation it will not look like the tuning test results noted above. This is due to the control being performed based on the results provided by the camera system mounted on the weapon's rotation mast. The camera used in the system is the CMUCAM3 by Carnegie Melon University. Previous versions of this device have effectively been black boxes with a command set including such things as blob detection and color detection. Version 3 gives the designer access to the internal code and is therefore considered an open-source device.

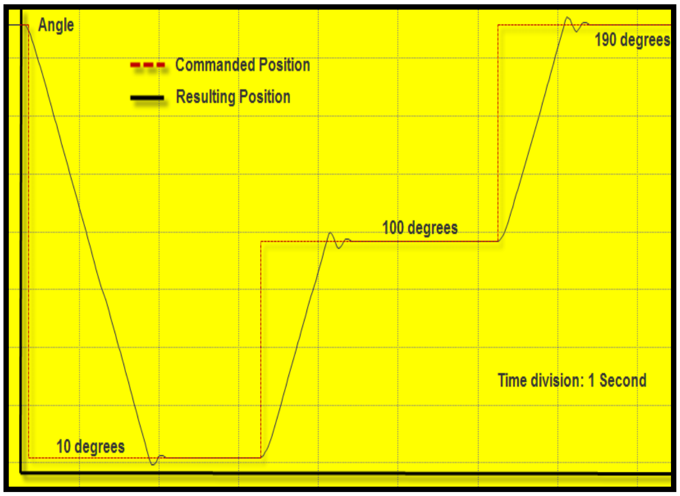


Figure 4. PID Control Results During Tuning Test

This allows more of the vision algorithm to exist on the camera and removes a significant part of the processing burden from our microcontroller. At the time of writing, the CMUCAM3 code is under development and near completion. The camera software was designed to return the center of mass and the blob size of a prescribed color (dark red) representing the desired target. Because the turret rotation also moves the camera, there is a 180-degree angle of view plus the inherent angle of the camera. However, since the weapon elevation system does not affect the angle of the camera, the weapon will be pitched to an angle dependant on the center of mass of the identified target in the vertical dimension taking into account projectile physics. Based on the area of the identified blob and given a known target size, the distance to the target can be calculated and used to consider projectile drop. Before firing, the turret will center the target in the view of the camera and pitch the weapon angle.

The Helicopter Design

Designs and control approaches on the Quadrotor were studied from research at the Australian National University, Stanford, The Swiss Federal Institute of Technology, Pennsylvania State University, Brigham Young University, and the University of Cambridge, to name a few [11-17]. Design of the helicopter for this study was based on the results of these other teams.

For the same reasons as in the sentry, all computing is completed onboard the aircraft via four multi-core microcontrollers yielding 32 independent computing units. Each of these microcontrollers has a specific task. The first of the microcontrollers, the IMU Microcontroller receives data from the onboard inertial measurement unit and communicates roll, pitch and yaw to the ZIGBEE Microcontroller. The ZIGBEE Microcontroller also receives communications from the GPS Microcontroller, which includes GPS, battery voltage and temperature data. Additionally, the ZIGBEE Microcontroller collects altitude information from a downward-looking sonar sensor. The ZIGBEE Microcontroller then communicates roll, pitch, yaw, battery voltage, temperature data, and GPS information to the MOTORS Microcontroller and transmits monitored data to the base station via a ZIGBEE wireless transceiver, where it is displayed on a monitoring television for safety and development purposes. The MOTORS Microcontroller uses the sensed and filtered data to determine the commanded motor speed for each of the motors. The MOTORS Microcontroller contains several PID loops, each operating on their own core to maintain a low iteration time. These loops control the roll, pitch and altitude.

Communications

The wireless communication chosen for the system was ZIGBEE. The choice to use a low data rate, short-range communication protocol was certainly purposeful. In many current military situations, cell phones and other personal devices are being used to trigger Improvised Explosive Devices (IED) because these devices are readily available, comparatively cheap, and the signal is reliable. If the system described herein relied on Bluetooth, Wi-Fi or another comparative technology, the individuals representing the targeted location could use a readily available device to break into the network, even with security measures, and intercept device-to-device transmissions. For example, many cell phones and other personal devices have Bluetooth and Wi-Fi capability but not typically ZIGBEE. In a future design, the wireless protocol used would likely be custom and utilize the latest anti-jamming and high-reliability technology, but since this research is not about wireless communications, the team chose to implement the best technology currently available and reasonably affordable.

Figure 5. Photograph of the Helicopter

Another piece of the design that will not likely exist in a future design is the base station monitor. This consists of a single microcontroller, a ZIGBEE device, a keyboard and a display device. This functions as the Command Center of the system and allows a full running view of both systems on one screen. This includes battery voltages, sensed temperatures, GPS locations, IR and sonar sensed values, IMU values, and weapon rotation and pitch angle values. The keyboard allows control of certain parameters in the system during the various testing phases but is not designed to be a remote control station.

Conclusions and Future Direction

Each day we progress further towards our goals and come closer to realizing the benefits a capable robot team can provide to the world around us. With military actions around every corner and governments wishing to put fewer soldiers in harm's way, a machine-driven solution is the ultimate goal. With the "Great Swarm" described here, a military action could be carried out by machine alone instead of soldiers, still in harm's way, using a remote-controlled robot designed to minimize harm to the soldiers that operate them instead of completely removing them from the situation. Of course, with these technological advances come numerous societal concerns regarding a robot revolt and other societal impacts that the automation of warfare has [18].

The team is further engrossed in the development of the sentry and the quadrotor. Test flights have been completed and control loop tuning is under way on the quadrotor system, while programming is underway on the sentry. For the sentry, some of the system-level components have been programmed and tested including the IMU components, weapon pitch and rotation, GPS and the motor controller communications. For the quadrotor, programming is nearly complete. Further research is required but a camera system is planned for the quadrotor such that it can "see" and locate the targets from the air. The authors expect to have a working relationship between dissimilar swarm members by early summer 2011 and hope to achieve mission completion late in the fall of the same year.

Once the single pair is complete and the team is able to test them through mission completion, the aim is to duplicate the individual devices so that closer imitation of swarming behaviors within like designs can be achieved. For the future, the team plans to continue to improve upon designs and focus on the common characteristics needed to be instilled within each member of all different swarms. These common behaviors are the key to having a swarm act appropriately to accomplish a greater goal. Without these common behaviors, it cannot truly be called a "Great Swarm."

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USING SOLAR ENERGY IN ROBOTICS AND SMALL-SCALE ELECTRONIC APPLICATIONS

Antonio Soares, Florida A&M University; Chao Li, Florida A&M University

Abstract

Now, more than ever before, the use of renewable energy is critical to the well-being of our planet. Solar energy, in particular, is one of the main sources of renewable energy and the subject of research worldwide. While most renewable energy projects using solar energy target large-scale applications, renewable energy technologies are also suited for small-scale applications. This is evident in hand-held calculators, recreational electronics and, more recently, traffic signals. One of the main issues encountered in the renewable energy industry, particularly the solar energy arena, is the storage of the harvested energy. The authors of this study developed a novel approach to the storage of solar energy for applications where weight may be a constraint. Particularly, the use of super capacitors is exploited as an alternative storage method for robotics and small-scale electronics. To this end, a solar-powered robot was designed and tests were conducted indoors using high-power light sources.

Introduction

The continuous discovery of novel materials used to fabricate the harvesting cells sustains the ambition of increased efficiency and the possibility of arriving at a global energy solution based on solar energy. However, solar energy is far from replacing conventional forms of energy used to supply the growing public and commercial demands. The highest market efficiency is about 24.2% and made available at a very high cost to the consumer. Incentives offered by states and the federal government encouraging residents to use alternative sources of renewable energy are having a negative effect on the solar industry by increasing demand and thus increasing the price to obtain the technology, especially in the private sector [1].

Exploring alternate sources of energy has become a priority amongst the scientific community. Recent oil spills, mine disasters and global warming have been the driving forces behind this ever-growing interest in alternative sources of energy throughout the world. Solar energy, in many ways, seems to be the obvious solution to the soon-to-be global energy crisis. The conversion of solar radiation into usable energy is still very expensive and inefficient. One of the problems is the power efficiency of materials used for fabrication of photovoltaic cells (PV) [2]. Storage of the harvested energy from the sun can also present an issue, due to losses and further processing such as conversion from DC to AC. For some applications, the energy is transferred directly to a grid system. In others, batteries are used to hold the converted energy. In very-small-scale applications, a capacitor connected to a solar engine maintains the voltage at a nearly constant level. For applications requiring higher energy and relatively light weight, this technique will not hold and the need for alternatives must be investigated.

This paper presents the results of a capstone project in Electronic Engineering Technology aimed at investigating an alternative way of storing solar energy for robotics and small-scale, lightweight applications. The background information necessary to understand the technology used for the design is presented, followed by a detailed design description of a solar robot used to investigate the feasibility of the project.

Design Description

The project is based on the IEEE southeast conference hardware requirements for the 2010 robotic competition. The robot had to be powered exclusively by solar energy, there could be no battery of any kind, and the robot had to maneuver on a course for a certain amount of time. The size of the robot was restricted to a maximum height and width in order to conquer height and width obstacles. The team had two minutes to harvest the energy from high-power lights and then three minutes to complete a course by traversing through and over certain obstacles varying in height and width.

Robot Design

The first prototypes of the robot were constructed by taking apart other robots, mainly Parallax Boebots, and using their components in lightly constructed frames. But it was concluded early on that using servos was not the best way to go as they are slow and consume quite a bit of energy along with the BS2 board used by the Boebot platform. In order to be successful, the design had to meet three basic interdependent constraints: structure size, navigation and power management.

After several prototypes, it was decided that with the amount of power stored during the initial stage, the number of obstacles to conquer would be compromised. The aim was to overcome the width and height obstacles and bypass the ramp obstacle. Even eliminating one obstacle, the design of the body was challenging.

The width and height had a great impact on the power, so tradeoffs had to be made. The panels produced more power when closer to the light source, but getting too high compromised the height obstacle. Having a heavy robot consumed power, but having it too light compromised traction and, thus, accuracy in navigation. Another parameter that dictated the shape of the body was the number of panels needed. Light wood was chosen for the frame and a "butterfly" look when placing the panels, as seen in Figure 1 (W=8", H=16", and L=25").

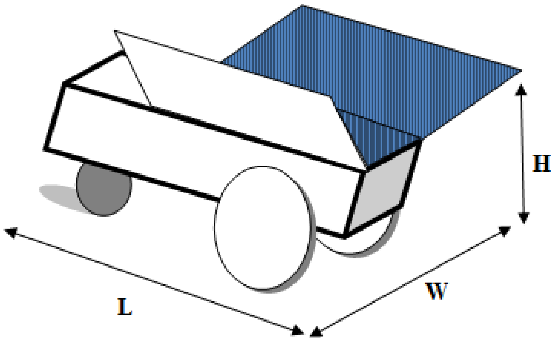

Figure 1. Block Diagram of Coolerbot Functionality

Navigation

In order to maintain the robot's trajectory, sensors had to be used. Again, dealing with such power restrictions, there was only so much one could do before the power would fall below levels required for motion. Most electronic sensors, such as ultrasonic and IR sensors, require some self-supporting power and normally consume compromising amounts of energy. So, in an attempt to conserve energy, mechanical sensors were implemented. There were whisker-like extensions from the frame with mechanical switches at the ends. In later stages of the design, IR sensors were implemented on both sides and on the front of the design. However, most of the navigation was accomplished through code-controlled subroutines.

The robot was controlled by the Pololu Orangutan LV-168 Microcontroller depicted in Figure 2a. It is a full-featured controller for low-voltage robots that can be powered with two or three 1.2-1.5V batteries while maintaining 5V operations for its Atmel mega168 AVR microcontroller and sensors. It is mounted on a small (2.15" x 1.9") module and includes two bidirectional motor ports, each capable of providing 2A (continuous).

The design made use of Micro Metal Gear Motors with a 150:1 ratio (see Figure 2b). These are very-low-power motors and can deliver a very high torque while maintaining a high speed. They have a long (0.365" or 9.27mm), D-shaped metal output shaft, and the brass faceplate has two mounting holes threaded for M1.6 screws (1.6mm diameter, 0.35mm thread pitch).

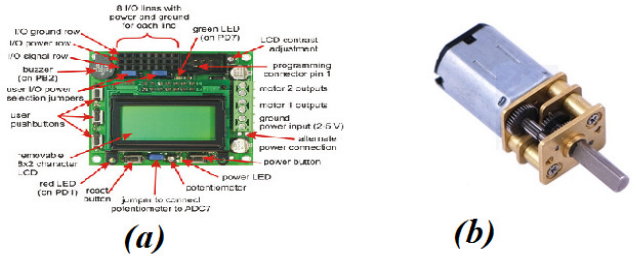

Figure 2. (a) Orangutan LV-168 Microcontroller, (b) Micro Metal Gear Motors

Power Management

An important piece of this design was power management. Many factors determined the type of power scheme used. The solar panels had to be efficient yet affordable; the capacitors had to be configured in a certain way for maximum performance; and, circuitry had to be introduced to manage or regulate the power.

Different types of panels were considered for the design. The first panel investigated was the rigid encapsulated solar panel rated at 0.9V 400mA, as shown in Figure 3a. It measures 2.5" X 3.75" X .25" and can be connected in series or parallel using small screws mounted on the embedded frame. Although the current was not bad, this panel had two problems: low voltage and a small surface area which called for more combinations. The second type of solar cell used was a thin-film module, specifically the 4.8V 100mA Flexible Solar Panel MPT4.8-150, shown in Figure 3b. Again, the power was not sufficient and the panels were cumbersome to connect due to a copper strip provided for the connections.

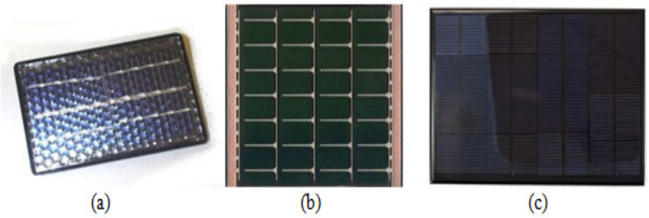

Figure 3. Solar Panels: (a) Rigid, (b) Flexible Thin-film and (c) High-Quality/High-Output

Finally, by a series of experiments involving height, capacitor combination and initial charge conditions, a more rigid and larger panel was chosen which could sustain the entire run shown in Figure 6c. The cell is a high-quality solar cell custom made for SparkFun Electronics, a site usually used by hobbyists. It is rated for 8V open voltage and 650mA short circuit, but has reached 9.55V open voltage and 850mA short circuit. The high output power was what the design needed, but some compromises had to be made such as the ones evident on topology. Termination is a 5.5mm x 2.1mm barrel plug, center positive on a 2m cable. It is a monocrystalline high-efficiency cell with a clear epoxy coating with hard-board backing.

One of the requirements for this project was that there should be no on/off switch. As a result, the microcontroller was altered to bypass the start button. This caused a problem because there is a point during charging where the microcontroller wakes up and starts pulling high current from the capacitor bank, which in turn slows charging and the robot cannot move. There is an initial potential barrier to overcome at start up requiring more charging capacity. At the same time, the initial charging time must be minimized in order to increase run time. The solution was to add two additional panels to the original two-panel configuration, all connected in parallel. This increased the charging capability of the system.

In order to get a speedy charge initially and still have enough power to run the field, several capacitor configurations were tested, of which one proved more efficient than the others. The capacitors used were 10-Farad super capacitors. Their small internal resistor allows for a fast charging time [3]. Combining them in a hybrid format (series and parallel) increased the charging time and slowed the discharge phase (when the robot is active).

Using Multisim 11.0 and Ultiboard 11.0, software packages from National Instrument, the circuit was simulated and laid out for in-house fabrication. Figure 4 shows the circuit diagram obtained from Multisim 11.0. As can be seen from the circuit diagram, there are two series banks. Bank1 is formed by C_1 in series with C_2, in parallel with the series combination of C_3 and C_4. Bank2 is formed in a similar manner. The final configuration is bank1 in series with bank2.

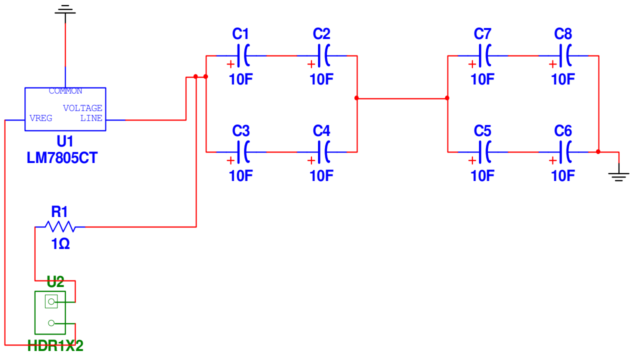

Figure 4. Multisim 11.0 Circuit Diagram

The circuit contains an additional voltage regulator and charging resistor. The regulator has an adjustable output and can regulate from 3.0V to an output between 5V and 12V DC. This regulator ensures that the microcontroller input voltage is maintained at the required 5 volts. A 1Ω resistor is used for charging-time minimizations [4]. Figure 5 shows the 2-D and 3-D circuit layout diagrams used in printed circuit board (PCB) fabrication. The final circuit and robot after fabrication of the PCB circuit are shown in Figure 6(a-c). The circuitry is housed under the panels.

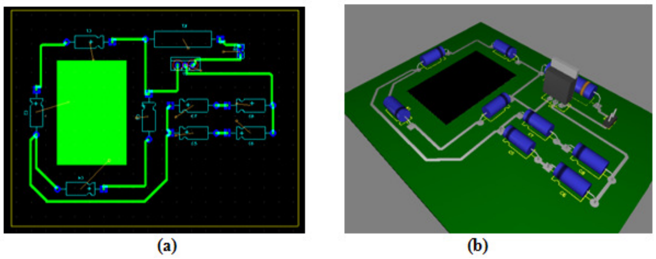

Figure 5. Ultiboard Circuit Schematic with Capacitor Combinations – (a) 2-D View and (b) 3-D View

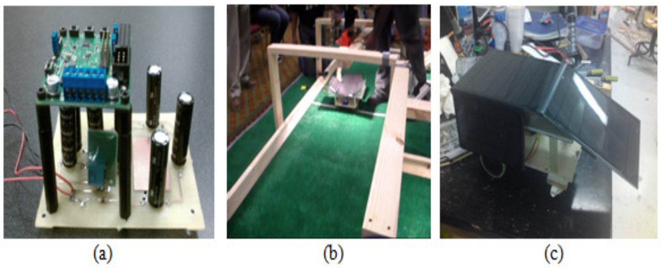

Figure 6. Final Design: (a) Circuit after Fabrication, (b) Robot Charging under a High-Power Light Source, and (c) Robot on a Lab Bench

Discussion and Conclusion

The final robot was able to charge up to 8.5 volts under the light source in about 1 minute. The charge stored in the capacitor bank was sufficient for the robot to reach the midfield point of a predesigned indoor field, where another light source was available for recharging. Navigation, however, proved to be a challenge once the design was moved from field to field. The dependency on code routines to navigate the robot through the field proved to be an issue. As the field texture changed, the robot deviated from the course because it required more power due to higher surface friction. The solution to this problem was the implementation of additional sensors to aid in navigation.

Tests were also conducted using natural sun as the source of energy by placing the robot outdoors. In the sunlight, the panels produced a large amount of energy and the addition of sensors was no longer an issue. The robot could run continuously as long as there was some sunlight available.

This capstone project made use of an unconventional method of energy storage that can be utilized in small, lightweight applications such as for robotics design applications. It shows that by combining super capacitors in hybrid formation and using additional circuitry it is possible to manage the solar energy stored in capacitors. The stiff constraints imposed by the design requirement used in this project clearly demonstrate that a combination of solar panels and super capacitors can be used to power small-scale electronics both indoors and outdoors. The configuration described here can supply small-scale devices that fall within the power ratings specified. However, for devices such as laptops, analysis shows that additional changes to the capacitor bank and circuitry are necessary. With advances in the photovoltaic industry, it is only a matter of time until laptops are self-charging by placing solar cells on the casing and using the same design approach discussed in this study.

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Biographies

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VIDEO-METRICS: CONDITIONED HEAD-TURN TECHNIQUES AND BEYOND

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Abstract

The use of the Head-Turn Technique (HTT) as a tool to measure human response to audio cues has been part of psychological research for some twenty years. The tool measures the participant's response to subtle changes in phonetics he or she is hearing by sensing the shift of the participant's attention focus toward the source of the phonetic stimulus. The existing tool has been largely unchanged since its inception. Previous proposals by this researcher presented enhancements to the test procedure; however, the methodology made use of rather primitive and now outdated technology. The tool, as it is, relies heavily upon human interaction, which may be contributing to inaccuracy of measurement and limitations in the types and richness of data that are captured.

In the existing process, a test administrator manually initiates the event prompting the change in the focus of the subject's attention. The occurrence or non-occurrence of a response is then judged by the test administrator. Computer control is limited to the generation of the phonetic stimulus. The proposed revision makes use of Video Image Capture (VIC) and video-metrics to provide more positive and more precise measurements. The enhancement will add the ability not only to detect the occurrence of the head turn event but also to time various aspects of the event. Computer software which is part of the project would track changes in gaze focus with millisecond accuracy. It could also measure the divergence between the orientation of the head and the focus of attention.

Discussion of the Head-Turn Technique in its Present Form

The present iteration of the HTT test process was developed for use in measuring infant and toddler responses to subtle changes in the phonetic composition of sounds to which the child is exposed [1], [2]. Figure 1 presents a plan view of the existing test layout showing one of the team members and the test participant. Figure 1 does not show the second test team member since that member is not present at the test location but administers the test from a remote location. As can be seen by examination of Figure 1, the toy waver is situated approximately 30 to 45 degrees to the participant's right, while a loudspeaker and display are 30 to 45 degrees to the participant's left.

The function of the toy waver is to maintain the attention of the test participant during the pre-stimulation phase of the test. Once the stimulation phase is initiated, the participant can be expected to shift his or her attention to the source of the stimulation which is the loudspeaker. Also not shown in Figure 1 is the test participant's parent, guardian or individual with whom the infant/toddler participant is familiar. The participant will be seated in the parent's lap so as to increase the likelihood that the participant will be comfortable and attentive during the test. The test set up is flexible so as to permit the participant to be seated independent of the parent, when this is practical.

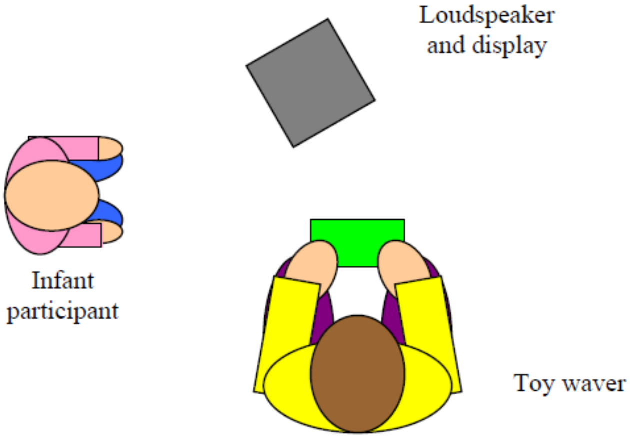

Figure 1. Plan of Test Layout

The process presently includes two test team members in addition to the test participant. The team is comprised of the test administrator and the toy waver. The test administrator's function is to manipulate the computer that generates the phonetic stream and records the responses of the participant. The phonetic stream is composed of a sequence of phonetic sounds that are presented as single syllables to the participant through a loudspeaker. In the sequence, a phonetic is repeated several times. At a given point in the sequence, the phonetic undergoes a subtle change, hereafter known as a phonetic change event. As an example, the phonetic "Lah" may be repeated until the test administrator initiates the phonetic change event. At this point, the phonetic "Bah" is repeated three times. This phonetic sequence may be better understood by examining Figure 2.

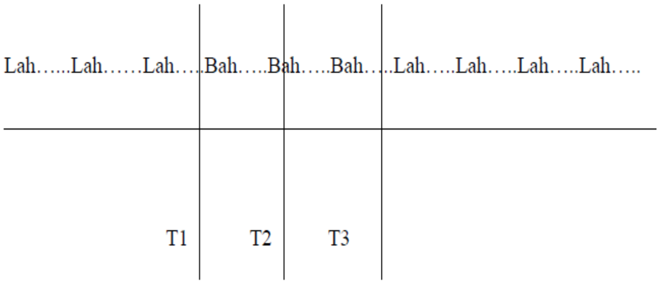

Figure 2. Test of the Phonetic Aspects of the Measurement

The times denoted as T1, T2 and T3 reference events which occur during the test. T1 denotes the change in phonetics used in the test. T2 occurs when the participant begins to move his or her head. T3 refers to the time when the participant's head is positioned at the stimulated orientation. The goal of the test is to detect the participant's reaction to the phonetic change event. Participant gaze reorientation, coincident with the phonetic change event toward the speaker from which the sounds are emanating, is recorded by the test administrator as a successful detection by the participant that a phonetic change event has occurred. The task of the administrator is a) to detect that a reorientation occurred and b) to ascertain that reorientation was a deliberate reaction of the participant to the phonetic change.

The toy waver's function is to attract and maintain the attention of the participant by use of actions and gestures with the toy, as shown in Figure 3. This orientation of the head and gaze toward the toy waver is referred to as the rest orientation or the rest position. In addition to these two members, the parent of the infant or toddler participant may be present to reduce tension in the participant. The test administrator is not visible to the toy waver, the participant or the parent of the participant. In this way, neither the toy waver nor the parent will know when the phonetic change event will take place. This is important since such pre-awareness might prompt the parent or toy waver to anticipate the movement of the participant's head with an inadvertent glance in the direction of the loudspeaker. Such actions have been demonstrated to be sensed by participants, a phenomenon referred to as gaze following [3]. Such gaze following would create an undesired control variable that would have a contaminating effect on the outcome of the test.

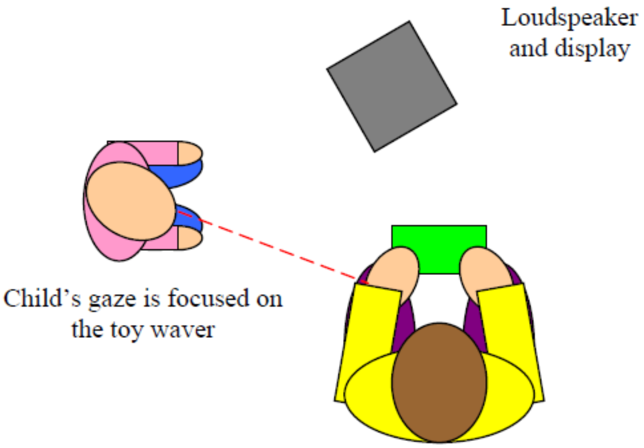

Figure 3. Participant's Attention Focused on the Toy

Test participants are males or females not younger than six months of age [4]. In the present test process, the infant or toddler participant is placed in the parent's lap in close proximity to the toy waver and to the loudspeaker and display. The toy waver maintains the concentration of the participant by showing the participant a toy, generally a stuffed animal [5]. Simultaneously, the computer software used to administer the test causes an audible repetition of a syllable which is common in the English language. An example is "Lah." The phonetic "Lah" is repeated at a rate of approximately once per two seconds. At an appropriate moment, the test administrator, through computer control, initiates the phonetic change event, at which point the repeated phonetic changes from "Lah" to another phonetic, "Bah," for example. The changed sound is repeated three times after which the software reverts back to the original phonetic.

With the change in the phonetic, the display that is on the same axis as the loudspeaker will present a picture of a stuffed animal. In this way the participant is presented with a pleasing stimulus as a reward for having noticed a change in the syllable that is being repeated. A head turn event is declared to have occurred when the participant deliberately shifts his or her attention to the speaker, as depicted in Figure 4, in reaction to the change in phonetic. This head and gaze orientation is referred to as the stimulated orientation or stimulated position.

Limitations of the Existing Test Regimen

In its present form, the test regimen makes use of a high level of human interface which limits accuracy and richness of the data that is captured from the test. Primarily, the occurrence of the head turn event is determined as the test administrator observes the movement of the participant's head from the rest position to the stimulated position. It may be difficult to declare with certainty that the event actually occurred or that a movement of the head was a result of the participant's detection of the phonetic change. In addition, no attempt is made in the present iteration to capture the time of the event. The importance of the detection and measurement of the latent times during the test shall be discussed later.

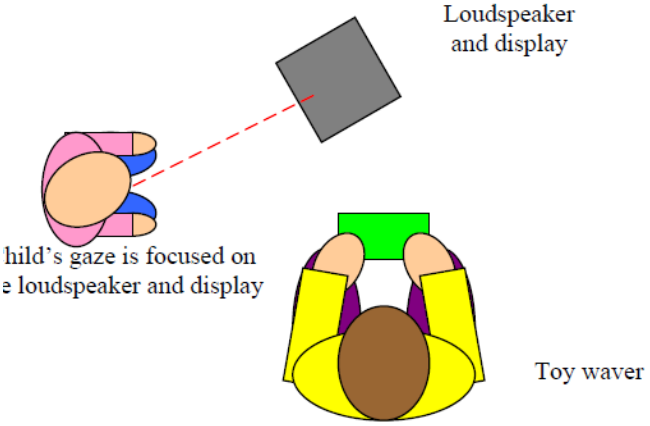

Figure 4: Participant's Attention Focused on Loudspeaker

The Revision

The research team envisions the application of video imaging and motion analysis, referred to here as video-metrics, to the task of providing highly accurate positional data based on the video capture of the participant's head as it moves from the rest position to the stimulated position. The field of video image analysis has assumed prominence in numerous disciplines such as security, sports and mechanical engineering. The research team has identified no project which intends to apply video-metric techniques to the HTT test process.

Lab Layout

In general terms, the technique involves making a video of the participant as the test proceeds using a digital video camera. The camera is interfaced to a computer which is running video image capture and analysis software. The image is sensed and quantified on a frame-by-frame basis. Instantaneous position of the participant's head is analyzed to detect movement or changes in position over time. The revised test setup will be comprised of the components as described below. The participant station will continue to include a position for the toy waver, the participant and the loudspeaker and display. The test station is separated from the administrator's position as in the present iteration. The layout of the lab is depicted in Figure 5.

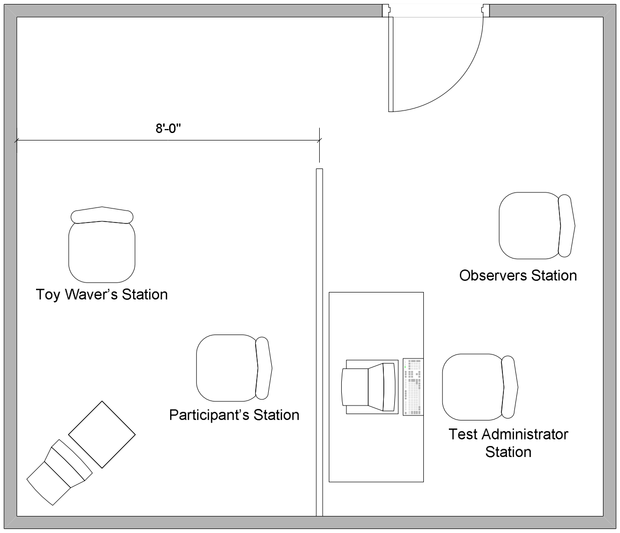

Figure 5: Plan View of Head-Turn Test Lab

The video camera will be situated in such a way as to be focused upon the participant and, more specifically, on the participant's head. This camera will be interfaced with a standard desktop computer located at the test administrator's position. In the present rendition, the single function of the computer is to control the transmission of the phonetic sounds to the loudspeaker. However, in the revision, the computer takes on most of the existing functions of the test administrator. In addition to controlling the audio, the computer will collect the video frames from the camera, process the video image frames, capture the metrics embodied in the frames, and store and display the data which emerge from the test. In addition, it is hoped that the test results will be presented in real time to the internet for viewing at remote locations.

Software Revisions

As previously stated, the existing test configuration makes use of computer support simply to manage the transmission of the audio stimuli. It is necessary to modify this software to provide additional capabilities as follows:

1. The revised software must embody a graphic user interface (GUI) that serves as a "dashboard" for the test administrator. The dashboard must give the test

administrator control over those functions necessary to conduct the test, store the test results, display the test results including an "instant replay" of the test video, mathematically analyze the test video from a time/event standpoint, and make the results available to external users including the Internet.

2. The revised software must be able to receive and process the video signal from the camera.
3. The revised software must be able to execute all functions of the existing software plus all of the functions of the test procedure as revised. This includes generation of the phonetic stimuli and timing management of the same, graphic presentation of the test participant focusing on movement of the head, control of the presentation of the toy on the display at the participant station, capture and analysis of the video image produced by the camera, storage of test results, replay of test results, generation and display of the timeline in a useable format, and statistical analysis of results of multiple iterations of the test.

The research team hopes to make use of off-the-shelf software for the video image analysis function. Another task which is part of the research is to tailor the available software for use in the HTT test environment. Additionally, the team will develop the GUI which will permit test administration and data analysis plus presentation of the test using the Internet. Generation, timing and control of the audio stimuli, as well as the image of the toy, should be a simple matter of configuration of the computer operating system. Researchers anticipate using Microsoft products for statistical analysis, storage and recall of test results.

Implications

As can be seen, the revision of the existing test proposed here provides users the ability to measure the speed with which the participant is able to process the perception of an audible stimulus and convert it to a completed head turn response. For the concept to be valid, accurate measurement of times and events must be an aspect of the regimen. This need for accuracy is predicated upon the premise that head position is an accurate indicator of focus of attention. This need not be assumed since Caron et al. [5] demonstrated the relationship in infants that have reached the age of 12 months. The proposed revision might facilitate measurements, suggested by Caron et al., of younger infants. Since a connection has been established between certain pathologies and impairment of the head turn function [6] the measurement of the times discussed above can be a useful diagnostic tool. Such conditions might be identified in participants. Therapies might be applied and then the effect of the therapies could be measured longitudinally by testing the head turn performance over time. The hereditary connection suggested by other researchers could he further explored [7].

There is cross-sectional value in determining the impact of various environmental factors upon such measurements. It may be inferred that the interval between T1 and T2 is useful in analyzing mental processing time. The interval between T2 and T3 could be an indicator of muscle control and optical/auditory performance. Indeed, there is potential value in the examination of head turn performance in older populations. The test setup permits the testing of such participants with little or no change in configuration and only minor changes in the test procedure. These are issues which will become more obvious as the revision is implemented; however, researchers anticipate the ability to measure the impact of substance abuse in participants as well as exposure to toxic or harmful substances. This has ramifications in the chemical and nuclear industries.

The technique could be applied to the Freiberg and Crassini [8] examination of infant sensitivity to sound power levels (SPL) with the addition of the ability to carefully measure absolute and relative sound power levels of the phonetic stimulus. The inquiry into an infant's ability to synchronize visual and audible stimuli by Hollich et al. [9] might be further facilitated by the enhancement to the Head Turn Technique.

In the initial proposal for enhancement [10], the research team established a standard for angular accuracy in the test results. The present proposal does not include a discussion of angular accuracy since part of the research will be to determine how angular accuracy may be established in the test procedure/setup. The benefits of attaching the angular accuracy discussed in the previous proposal will be discussed in future reports on the research as the project proceeds.

Conclusions

The disciplines involved in this project include video image capture and analysis, high- and low-level programming, audio signal technology, system analysis and project management. In addition, the application of test results is applicable to the social and medical fields. When applied to adults in the workplace as discussed above, HTT can serve as a tool to gather data for management or social programs. The test has broad applications in a wide range of disciplines. There are interesting implications for future research attaching to angular accuracy, which will find its genesis in the present project.

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Biographies

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LEAN AUTOMATION: REQUIREMENTS AND SOLUTIONS FOR EFFICIENT USE OF ROBOT AUTOMATION IN THE SWEDISH MANUFACTURING INDUSTRY

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Abstract

Globalization, demographic changes and environmental challenges are putting strong pressure on the European manufacturing industry and increasing demand on resource efficiency, sustainable manufacturing, innovative and individualized products. Today, Swedish manufacturing in mature traditional sectors is increasingly migrating to low-wage countries such as China and India. There is a strong need for the manufacturing industry in Sweden to enhance the ability to develop and manufacture products competitively. One way could be through an increased level of automation and increased use of industrial robotics. However, robot automation investments are in many cases regarded as too expensive and too technically advanced, especially within small and medium-sized enterprises. The objective of this study was to investigate requirements and possible solutions for the efficient use of robot automation in the Swedish manufacturing industry. Results from the two research projects tied to this study are presented here. In the first project, requirements of automation solutions within small and medium-sized manufacturing companies were analyzed. The second project looked at the development of possible solutions for increasing the reconfigurability of robotic systems, thereby enabling production of different products and simple configuration to handle future product variants without large additional investments.

Introduction

Globalization and the increasing challenge from low-wage competitors highlight the need for Swedish manufacturing industries to enhance their ability to develop and manufacture products competitively. This competitive climate is described by ManuFuture, which is a European Technology Platform specifying important development areas for future production systems, called the Strategic Research Agenda [1]. One of their conclusions was the development of future knowledge-based factories which would require research into adaptive structures and solutions that would provide for continuous change. Some examples of such structures and solutions include 1) management models and systems following the objectives of self-organization and self-optimization, 2) reconfigurable technical systems and integrated processes/systems, 3) technical intelligence in process control systems with efficient human-machine interfaces, and 4) efficient networking in systems based on standards and open-system architecture [1].

One way to handle the current manufacturing challenges and improve a company's efficiency could be to invest in automation and industrial robotics. Ever since the first industrial robots were launched to help, mainly in the automotive industry during the early 1960s, the robot has been used to replace humans in work environments unsuitable for humans due to, for example, heavy lifting, monotonous movements or hazardous conditions [2]. Long accepted by industry as a method for improving quality, performance and efficiency, robotics has for at least three decades been a key technology in manufacturing industries [3], where is has been employed in order to increase industrial productivity and competitiveness in manufacturing. Highly automated production systems with a limited amount of manual work will enable countries with high labor costs, like Sweden, to compete globally [4].

However, robot automation is in many cases regarded as too expensive and too technically advanced, especially within small and medium-sized enterprises (SMEs). Research shows that many SMEs have little confidence in their ability to implement changes in the robotic working cells [5]. SMEs also feel uncomfortable having to rely on outside experts in order to handle day-to-day activities such as introducing new products or fixing small problems.

Another question and debate within industry is whether traditional robot automation fits the principles and practices of lean, which many manufacturing companies currently are trying to implement. When conducting interviews in industry, one can receive comments like: "Automation and industrial robotics create complexity" or "Robotics and lean do not fit together; rather, they contradict each other". In some cases, companies have even started to remove automation, motivated with a reference to Toyota as a company that does not use advanced manufacturing technologies. Thus, another challenge is the adaptation of automation to the principles and practices of lean production [5].

Based on the aforementioned challenges, the overall objective of this study was to investigate the requirements and possible solutions for the efficient use of robot automation in the Swedish manufacturing industry. Results from the two research projects tied to this study are presented here and show how industrial automation and robotics can increase manufacturing competitiveness in industry. In the first project, requirements of automation solutions within SMEs are analyzed. The second project looked at possible solutions for increasing the reconfigurability of robotic systems, thereby enabling production of different products and simple configuration to handle future product variants without large additional investments.

Research Method

This paper presents results from two research projects which were based on a case study research methodology, including interviews, direct observations and, to some extent, practical development in industry. A case study is a preferred research strategy when a specific phenomenon is to be closely studied within its natural context [6]. Case studies can be characterized by the fact that they often look at phenomena when and where they occur and that the exact context or delimitations are not fully known [6]. The two research projects included both literature studies of theory related to lean manufacturing and automation, as well as empirical data collection from industry.

During the first research project, an analysis was done on the requirements on automation solutions within small and medium-sized manufacturing companies. The evaluation and analysis was based on 45 case studies, performed at different SMEs in the region of Eskilstuna, Sweden, between the years 2005-2009. These case studies were executed within the manufacturing system with the objective of investigating the possibilities of using robot automation to improve industrial competitiveness. These studies were part of the Robots to Thousands (RTT) project within the Robotdalen program in Sweden [7]. The studies were executed by engineering students from a masters program within “Production and Logistics Management” at Mälardalen University, supervised by a research team at the university investigating the use and application of robot automation within SMEs. A simply, standardized methodology was used for the studies and based on four different project phases: 1) problem specification, 2) process definition, 3) actual status in the area being studied, and 4) suggested solutions and an investment analysis. Each study was documented in a report based on a standardized structure. These reports were then analyzed, the results of which are presented in this paper. The analysis consisted of comparing the specified reason and problem in the study (i.e., why the company wanted to invest in automation), the potential of investing in robot automation, and the identification of the main obstacles and reasons for not implementing robot automation in each case study.

The second research project revolved around the investigation of the concept of mobile production capacity on demand. The idea with mobile production capacity is to use mobile manufacturing modules that can rapidly be combined into a complete manufacturing system and be reconfigured for a new product and/or scaled to handle new volumes. Given such a module, the production capacity could be offered as a mobile and flexible resource that can rapidly be tailored to fit the needs of the customer. The Swedish Foundation for Strategic Research funded the research project, which was named “Factory-in-a-Box”, between the years 2005-2009. The main objective of the project was to demonstrate the concept of mobile production capacity on demand through the development of real industrial demonstrators in close cooperation with academy and manufacturing companies in Sweden.

One of the demonstrators developed for this project focused on reconfigurable robotic solutions and started as a development project that resulted in a prototype solution that was implemented as a functional robotic cell within a manufacturing company [8]. Another demonstrator was developed at a small Swedish manufacturer with a profile of craftsmanship and small production volumes. The aim was to investigate the possibility of using robot automation in combination with the Factory-in-a-Box concept in order to quickly ramp-up production through portable robot solutions and increase the flexibility of the manufacturing system [9]. Both demonstrators were developed by a research team from Mälardalen University.

Automation and Lean Production

Current research shows that companies that implement lean manufacturing principles or just-in-time production (JIT) often have a competitive advantage over those that do not [10]. However, implementation of a lean production philosophy is more or less successful depending on how much the internal structure and culture of the company is changed [11]. Many western companies have realized that just trying to imitate the Toyota Production System will not give them the advantage they are looking for. Many companies are realizing that they need to implement lean within the “whole” organization; that is, they need to become a lean enterprise [12]. The term lean is often related to using less human effort in the factory and less manufacturing space, having fewer investments in tools and fewer engineering hours needed to develop a new product in less time, keeping less inventory, having fewer defects in production, and producing a greater and ever-growing variety of products [12].

Technology as automation affects competitive advantage if it has a significant role in determining the relative cost position or differentiation [13]. Since technology is embodied in every value activity and is involved in achieving linkages among activities, it can have a powerful effect on both cost and differentiation. Traditionally, high-tech automation has been used by companies that were not considered as lean [14], while companies such as Toyota have developed so-called low-cost automation [15].

Automation in lean production is about deciding the appropriate level of automation [16].

> It's not a question of whether lean is manual or not - effective lean production systems use both manual and automated processes - the task is to determine the appropriate type of automation. Taichi Ohno, the co-inventor of the Toyota Production System, said long ago that there are two sure facts about forecasts: they are almost never correct, and they always change. With this thought in mind, machines need to be developed so that the lean production system can have increments of capacity without a large capital expenditure. In other words, how can automation be developed within the production system to react to changing customer demand? (p. 1)

The phrase "lean automation" has been defined in different situations. Some pharmaceutical industries have been looking to make their production more efficient through the use of automation and have, in this context, defined lean automation as [17]:

> Lean automation is a technique which applies the right amount of automation to a given task. It stresses robust, reliable components and minimizes overly complicated solutions. (p. 26)

One of the pillars of the Toyota Production System is called jidouka, which means autonomation, also known as "automation with a human touch". The original meaning of jidouka was Automation, as shown in Figure 1. The sentence was later changed at Toyota into the spelling shown in Figure 2, the pronunciation of jidouka was the same but they added two extra lines, spelling human. This was an important statement, meaning that the automation (or autonomation) should be working the same way as a human; it should be intelligent. The three words in Figure 1 spell out "self moving transformation", while the extra two lines in Figure 2 add the human touch.

The purpose of the addition of human touch was to ensure that production would stop if there were any type of problem during production. The concept of autonomation was developed because Toyota saw a potential problem in normal automation; that is, that it does not have any built-in checking for quality problems. This could lead to hundreds of defective parts produced if automated production equipment were operating without human supervision. "At Toyota, a machine automated with a human touch is one that is attached to an automatic stopping device" [18]. This means that autonomation is an important part of the Visual Control system, or Management by Sight, where it is important that the current state of production is always visible and any problems are brought to attention as soon as they occur [19].

自動化

Figure 1. The Japanese Word Jidouka for Automation

自働化

Figure 2. The Japanese Word Jidouka for Autonomation

A conclusion regarding the discussion on automation in lean production is that a lean philosophy introduces extra demands on the workstations in the production system. Automation adopting lean principles should not reduce flexibility and robustness of the system. Lean automation uses robust, reliable components and minimizes overly complicated solutions. In order for automation to fit lean principles and practices, there is a need for development of solutions giving increased availability, reducing set-up times, improving the ability for easily reconfiguration, and offering information design to clearly present visual information and options to the operators. Thus, a possible development of robot automation towards Jidouka and "automation with a human touch" could be to give information support to operators, thereby reducing the perceived level of complexity.

Research Project 1: Automation Requirements within SMEs

Analysis showed that the main reasons for companies to address a possible implementation of automated equipment were to:

- reduce manual costs within operations (78% of all studies);
- remove ergonomically bad workstations and operations (38% of all studies);
- improve quality and achieve higher utilization (29% of all studies); and,
- reduce lead time/through-put time in operations (16% of all studies).

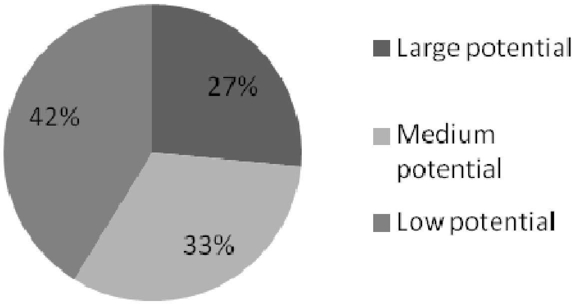

Figure 3. Investment Potential of Robot Automation to Increase Manufacturing Competitiveness within Swedish SMEs

The results from the analysis indicated that robot automation is not easily justified within Swedish SMEs. Robotic automation is often regarded as a large investment, which often is hard to justify beforehand. The reason for this is that many of the SMEs have a rather short planning horizon when it comes to product lifetimes. Many of the companies are sub-suppliers with small batch sizes. Although the total order size can be rather large, it is often divided into several smaller orders, making it more difficult to predict the total number of articles that should be produced.

The analysis consisted also of analyzing the main obstacles to economically justify the investment, as well as expressed reasons not to invest in robot automation:

- Low and unsecure volumes (56% of all studies)
- Short life-cycles, product variety and costs to reprogram the system (38% of all studies)
- Reluctance in investing in advanced technology and the need to rely on external experts (31% of all studies)
- Costs related to the need of flexibility and reconfigurability (24% of all studies)
- Problems regarding the handling of breakdowns and maintenance (16% of all studies)

Many of these obstacles/reasons are related to each other; for example, low production volumes, short product lifecycles and the need for flexibility as well as advanced technology and problems regarding handling maintenance. Based on the analysis, one could conclude that there is a need to reduce costs related to a perceived level of complexity in order to justify more investments in robot automation in SMEs.

The analysis of the different studies within SMEs also showed a need for support for:

- determining the right level of automation as well as specifying the automation solution;
- handling a lack of reliable data when analyzing operations in SMEs; and,
- investment analysis related to product life-cycles and the balance between flexibility and reconfigurability.

Another conclusion from this study was the need for a simple and structured systematic approach/methodology for investigating the possibilities of using robot automation to improve industrial competitiveness within SMEs. This ended up being a good requirement specification of a future robot system solution that could be communicated and handed over to an integrator.

Research Project 2: Two Automation Demonstrators

This research project investigated the concept of mobile production capacity on demand and a concept called Factory-in-a-Box between the years 2005-2009. The goal of the project was to develop industrial demonstrators in close cooperation with academy and manufacturing companies in Sweden.

There are several potential applications of mobility and production capacity impacting demand within the manufacturing industry, including

- covering occasional production volume peaks;
- performing maintenance close to the customer by moving equipment;

- sharing investments by moving equipment between plants;
- quickly facilitating prototype development close to product development; and,
- leasing of equipment for temporary use.

In the Factory-in-a-Box project, standardized production modules were developed with the overall objective of developing solutions and means for easy re-configuration of manufacturing systems and supply chains. Two industrial demonstrators involving the use of robotic automation and trying to realize and demonstrate the Factory-in-a-Box concept, were developed.

One of the demonstrators focused on reconfigurable robotic solutions and included the investigation of if and how reconfiguration of a robot system could be supported by software. A survey of the market of available PC software that could meet the requirements of the industrial application was conducted, but no suitable solution was found. The decision was made to develop software that could meet the industrial needs of reconfiguration, which led to the design and implementation of a prototype, called the Cell Configurator [20]. This software supported the configuration of the program logic in the working cell with an easy-to-use and intuitive drag-and-drop programming style.

The demonstrator developed within the project consisted of two robots cooperating together with other I/O-controlled equipment such as a gluing station and a folding station. The programming of the logical sequences of the cell was implemented as a graphical user interface enabling the user to program the logical sequences in the programs as icon-based flowcharts. This type of graphical programming has been shown to be more visual to the user and more intuitive to use. The programming of the robotic movement paths was implemented using simulation tools and some online programming. This installation was put into production at the industrial partner during the autumn of 2006. The demonstrator started as a development project, resulting in a prototype solution and finally an implementation of a functional robotic cell in production within the company.

The key features and vision of the Cell Configurator software is that it may be used for several different robot applications, enabling the user to have the same software solution and user interface on all its robot installations. Reconfigurability is enabled as it lets the user change the program logic of the cell in a swift and intuitive way. Also, long-term adaptability as a set of plug-in interfaces allows the user to create its own components and import them into the software. This allows the user to use any peripheral equipment that can be used programmatically and also to use any type of robot controller as long as its resources may be accessed from the PC.

A second demonstrator was developed at a small Swedish manufacturer with a profile of craftsmanship and small production volumes, with a potential of a future volume increase due to success in products and market. The aim of the study was to investigate the possibility of using automation in combination with the Factory-in-a-Box concept in order to quickly ramp-up production through portable robot solutions which increase the flexibility of the manufacturing system. The study resulted in a Factory-in-a-Box demonstrator, which was physically presented in December 2008 in Eskilstuna, Sweden.

The demonstrator set out to investigate whether automation in combination with the Factory-in-a-Box concept could be a suitable solution for how to increase the production volume of craftsmanship and small production volumes at the case company. The initial phase of the project included an initial process mapping at the company and the generation of different conceptual robot solutions. The initial conclusion of the feasibility study was that a fixed automation solution was most appropriate, if the production volumes could rise to planned levels. Still, the company wanted to keep the image of craftsmanship as a part of the trademark of the products and company. This made investment in fixed-process automation in the production process hard to justify. Further, as the company was run by only two people having competence in the manual process but no knowledge in production engineering or automation technologies, this made investing in advanced production technology risky. Thus, the main objective was a portable robot solution with a focus on simplicity and usability, to be able to guarantee smooth and fast installation.

The results included standardized equipment that could be reused for other purposes. The use of an industrial robot made the cell flexible since its range of possible applications is vast and new tasks could easily be added. The user interface, on a PC screen, was made as simple as possible to enable easy handling of the cell even for persons not familiar with industrial robot systems. For example, a touch screen was used to manage start/stop functions and the choice of labels. The use of parameterized programming made it easy to change the programming and the cell behavior. The robot was placed on a platform that, due to its weight, would not need to be secured to the floor. The small size of the cell (2774×1868×2000mm) also enabled it to fit into many environments, which was a requirement if the cell were to be leased to different customers.

Some of the conclusions from the two demonstrators presented here include:

- It is technically possible to reduce the perceived level of complexity in automation equipment by using software support and intuitive control through, for example, graphical programming.
- Portable and mobile equipment enables new commercial solutions such as leasing, which removes some of the obstacles and risks regarding investments at SMEs.
- Standardized and reusable solutions are crucial factors in achieving simple automation solutions, enabling easy reconfiguration and changes of the system to handle future product variants without large additional investments.

Requirements and Solutions for Lean Automation

The objective of this study was to investigate requirements as well as possible solutions for efficient use of automation in the Swedish manufacturing industry. It was stated that one way to handle current manufacturing challenges and improve a company's efficiency could be an increased level of automation and increased use of industrial robotics. However, robot automation investments are often regarded as too expensive and too technically advanced, especially within SMEs. Another challenge was the adaptation of automation to the principles and practices of lean production, which many manufacturing companies currently are trying to implement.

Automation within lean production was discussed, indicating the need for robust, reliable components as well as to minimize overly complicated solutions. In order for automation to fit lean principles and practices, there is a need for development of solutions giving increased availability, reduction of setup times, improvement in the ability for easily reconfiguration and information design to clearly present visual information and options to the operators. A possible development of robot automation towards Jidouka and "automation with a human touch" could be to give information support to operators to reduce the perceived level of complexity.

There is, based on the research projects presented in the paper, no reason to say that industrial robotics is not a suitable solution. However, as companies strive to become leaner and eliminate waste, complex production equipment could cause other problems in the automated process due to rigid solutions and limited transparency. Continuous flow and reduced inventory highlight inefficiencies and pose new demands on the equipment used in the production cells. The research projects presented in this paper enumerated possibilities for reducing the perceived levels of complexity in automation equipment by using software support and intuitive control via techniques such as graphical programming. Portable and standardized solutions that could be reused would be one step towards making automation more accessible.

Based on the discussion of automation and lean production as well as the empirical studies presented here, four main areas for future research are proposed that would enable more efficient use of automation in the Swedish manufacturing industry. These four areas were also proposed as central themes in the development of a lean automation concept.

1. The ability to choose the right level of automation as well as the right automation solution. These are important challenges in the development phase of an investment in automation. Knowledge and support in this area will enable the formulation of a good specification of a future automation solution.
2. The ability to develop automation solutions which are flexible and reconfigurable, enables the system being developed to be changed and adapted to new demands during its lifecycle. This requires hardware and software solutions for changeovers and changes of the automation system towards new products and new applications.
3. The ability to handle complex equipment without being an expert. The requirements are intended to reduce the perceived level of complexity, possibly through intuitive user interfaces.
4. The ability to change and implement changes in a given automation system due to changes in the products. This should be done by the owner of the equipment without large additional investments in, for example, expensive service contracts. This requires support during operations by the system integrator. If the right hardware and software solutions are chosen, the changes could be easy; otherwise, some sort of help-desk function would be needed giving online support when needed.

Summary and Conclusions

The objective of this study was to investigate requirements as well as possible solutions for efficient use of automation in the Swedish manufacturing industry. Results from two research projects were presented, which investigated how industrial automation and robotics can increase manufacturing competitiveness in industry. In the first project, requirements on automation solutions within small and medium-sized manufacturing companies were evaluated. The second project investigated possible solutions for increased flexibility and reconfigurability of robotic systems enabling production of different products and the adoption of future product variants without large additional investments.

Four main areas for future research were proposed as central in the development of a lean automation concept; 1) the ability to choose the right level of automation as well as the right automation solution, 2) the ability to develop automation solutions which are flexible and reconfigurable, enabling the system developed to be changed and adapted to new demands during the life cycle, 3) the ability to handle complex equipment without being an expert, and 4) the ability to change and implement changes in a given automation system due to changes in the products.

Future work will include development of support for choosing appropriate automation levels and automation solutions and developing a robot automation handbook. This handbook will give support to the development phase when investing in automation solutions and could include checklists and theoretical guidance on the development work. The pre-studies performed in the Robots to Thousands (RTT) project within the Robotdalen program in Sweden, is a good base for this work.

The ease-of-use part in handling the equipment as well as handling changeovers will be investigated through the development of a cell-PC software tool which will enable monitoring of the production process in the cell. This solution will provide statistics and system awareness during production to the operators and also providing functionality for alerting the operator regarding operator maintenance and changeovers between products. Later, methods for systematic robot programming will be introduced, aiming at simplifying and visualizing robot programs which are easy to modify through, for example, parameterization. The overall objective of the ease-of-use area is to reduce the perceived complexity of the manufacturing system supporting reconfigurability of robotic systems and enabling production of different products and simple configuration to handle future product variants without large additional investments.

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USING THE MEASURED FREQUENCY RESPONSE FUNCTION OF A DRILLING RIG TO MODEL ROCK SURFACE TOPOLOGY GENERATED BY A CORING BIT

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Abstract

Rock drilling is utilized in oil and gas production as well as geothermal energy development. Drilling bits encounter severe vibrations and are subject to failure. Several schemes were developed to study bit-rock interaction under dynamic drilling conditions. One such scheme was to utilize the frequency response function (FRF) of the drilling system to model the system's dynamics. This study looked at how this approach could be applied using a drilling platform, referred to as the Hard Rock Drilling facility (HRDF), developed at Sandia National Labs in Albuquerque, NM. It will be shown how the measured FRF of the HRDF can be utilized to predict bit forces and vibrations under varied drilling conditions. Moreover, the methodology was used to model rock surface topology and compare the results with test data obtained in the laboratory.

Introduction

In recent years, oil and gas wells are being drilled ever deeper in order to reach untapped reserves. The long drill strings needed for such wells are, however, more susceptible to vibrations induced by instability. To study these vibrations, simulation of the drill string, bit and rock interaction was employed. Moreover, test rigs and measurement-while-drilling (MWD) systems were used to validate simulation results [1-3].

A drill string is essentially a long series of pipes connected together with a bit at the end making it so flexible that it behaves as a string, hence the name drill string. This flexibility is the root cause of excessive vibrations. These vibrations take place in three-dimensional space, namely axial, torsional and lateral. Lateral vibrations are controlled through track bits and the placement of supports close to the bit [4], [5]. Torsional vibrations are the most destructive because they lead to bit movement in a backward direction relative to the rock, which leads to breakage of the cutters. Replacing the bit requires removal of the drill string, an expensive process. It was shown that torsional vibrations can be controlled by controlling axial vibrations. This is because controlling axial vibrations keeps the bit firmly against the rock and does not allow the torsional energy to be released [6]. Control of axial vibrations can be accomplished by employing a shock absorber (referred to as shock sub) above the bit [7], [8]. Some of these shock subs are quite sophisticated and involve active damping [9], [10]. Another approach is to match the bit to the drill string. Both of these approaches require an analysis of drill string modes.

Generally, drill string vibration can be loosely classified in two broad categories: forced and self-induced. Forced vibrations have frequencies that are speed dependent and increase as the force increases and die out if the force is invariant with time. On the other hand, self-induced vibrations have frequencies that are system dependent and can exist in the presence of a steady force and may increase or decrease with time. Self-induced vibrations, sometimes referred to as chatter, were shown to exist in drill strings equipped with polycrystalline diamond compact (PDC) bits, particularly in hard rock. This was demonstrated in laboratory drilling at the HRDF [11].

A fundamental question pertaining to self-induced vibrations is: What is the underlying cause of this type of vibrations? The answer to this question is basic to understanding self-induced vibrations. This question can be answered by considering the bit and drill string as a feedback control system. A constant force, say the weight-on-bit, is applied to the bit which is forced to rotate. The bit reacts by moving in the axial, rotational and lateral directions. This movement affects the interaction between the bit and rock surface. This in turn produces a dynamic force and again alters the bit displacement. As the bit moves over the rock surface, it is removing material that has been shaped by previous passes. If, for simplicity, we envision the surface to be sculpted in a harmonic fashion, the critical variable determining variation in material thickness is the phase shift between the current bit movement and the wave caused by material removal by the preceding cut (see Figure 1). In other words, the phase shift (ε) between the forward path (current bit vibration) and feedback signal (surface shape due to previous bit vibration) determines whether vibration in the bit grows (unstable system), dies out (stable system) or remains unchanged (limit of stability or quasi-stable).

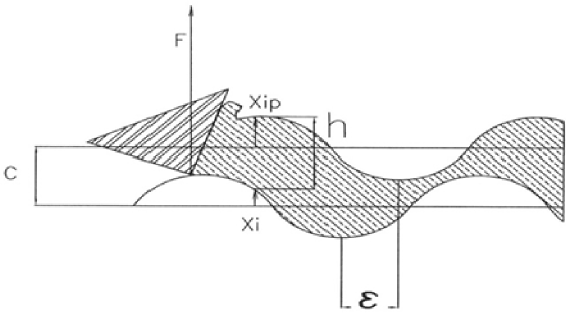

Figure 1. Model of Rock Surface

Simulation of bit vibration for an assumed drill string can distinguish operating conditions where the system is stable or unstable. One can also find conditions where the system is at the limit of stability, or quasi-stable, and a precise limit between the two states can be calculated. A modal model is used to obtain the dynamic modes of the drill string. This model is used to predict drill string stability in one of two ways. First, to obtain a stability boundary, referred to as the limit of stability [12-14]. It shows the bit diameter at each speed above which the drill string becomes unstable. Second, a time simulation can be used to predict bit behavior under varying drilling conditions.

Factors affecting rock surface topology are bit geometry, system dynamics, rock type and operating conditions. The thrust of this study was to show how these factors could be used to predict rock surface topology produced in a drilling rig and to compare these results with those obtained in the laboratory.

Background

Many designs for laboratory rigs have been employed to test drill bits. A novel approach is given by Elsayed [15]. Sandia National Laboratories (SNL) built a testing facility to test PDC drill bits. The original intention was to test for cutter wear. It was later realized that most PDC bit failures are not due to cutter wear, but rather impact loading caused by unstable drilling. To test for such conditions, flexibility was added to the drilling column in the axial and torsional directions. This facility is referred to as the Hard Rock Drilling facility (HRDF), as shown in Figure 2. Different types of rock and bit designs were tested. This study examined test results from the coring bit shown in Figure 3a.

A coring bit essentially produces a core which reduces the cutting surface compared to other bits of the same size. Consequently, a coring bit requires less cutting force, resulting in higher penetration rates. This coring bit has an inner diameter of 31.04mm and an outer diameter of 83.26mm. It utilizes three cutters whose diameters are 26.82mm and which are placed at a 20-degree negative rake angle. The cutters are placed at 0° from a reference line (inner gage cutter), 155° CW (intermediate cutter) and 246° CW (outer gage cutter). Figure 3b shows a cross section of the bit with the three cutters rotated to fall into the same plane. Notice that the cutter profile travels a distance (*hav*) per revolution. The area of rock cross-section is simply (*ro-ri)hav* or (*b hav*). The bit force is then similar to that of a radial bit with one blade whose radius is the bit width (*b*). This is a good approximation considering that the overlap between the areas removed by adjacent cutters is minimal [14].

Figure 2. Sandia's Hard Rock Drilling Facility (HRDF)

Figure 3a. Coring Bit

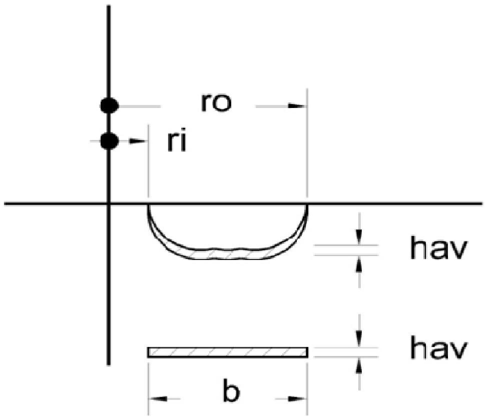

Figure 3b. Coring Bit Model

Problem Statement

In this study, Sandia's HRDF, shown in Figure 2, was used as a drilling platform. System dynamics were introduced through the frequency response function (FRF) of the HRDF measured in the axial direction at the bit. Coring bit geometry, shown in Figure 3a, was included in the analysis in order to obtain the stability diagram. The rock used for drilling was sandstone with a Specific Power (work per unit volume to remove rock) of 6,500 psi. This data was used to simulate both stable and unstable drilling and show their effects on rock surface topology. Finally, a comparison was made between the simulated topologies and more typical ones obtained from drilling in a laboratory.

Methodology

In this section, the methodology utilized in this study will be outlined. First, the concept of stability will be defined and applied to the HRDF. Also, the equations used to obtain the bit diameter at the limit of stability will be presented. The dependence of these equations on the real component of the frequency response function will be shown. This will be followed by a presentation of the HRDF model used in calculating bit forces and vibrations under stable and unstable drilling conditions. A parameter identification model for the FRF of the HRDF will also be presented in the time and Laplace domains. This model in turn will be used to plot the stability diagram, which is essentially a plot of bit diameter against bit speed at the limit of stability. Additionally, combinations of bit diameters and speeds on the limit of stability, as well as in the stable and unstable regions, will be identified. Bit forces and vibrations were calculated and plotted at these drilling conditions. Finally, bit vibrations were used to model rock surface topology under these varied drilling conditions.

Stability of the HRDF

The first approach to stability analysis is to use formal equations for the stability diagram. This approach is based on the concept of feedback inherent in self-induced vibrations. A bit force causes the bit to oscillate in the rock. This causes variations in rock surface topology. When bit cutters enter the rock, their forces are influenced by that variation in rock geometry. This in turn affects bit vibrations, and so on in a feedback fashion. If this feedback is favorable, the drill string is rendered stable; if unfavorable it will be unstable. The quasi-stable states represent the limit of stability [12-14]. The key equations of stability are given below:

$$b_{lim} = \frac{-1}{2mK_S Re} \tag{1}$$

$$\varepsilon = \left(\frac{f}{mn} - N \right) \tag{2}$$

where:

b_{lim} = $(r_o$-$r_i)$ at the limit of stability (m). See Figure 3b.
m = Number of cutter rows in bit, taken as (1) as shown in Figure 3b.
K_s = Rock Specific Power (N/m^2)
Re = The real component of the Frequency Response Function (FRF) (m/N)
f = Vibration frequency (Hz)
n = Bit speed (rev/s)
ε = Phase shift (degree). See Figure 1.
N = An integer 0,1,2…etc.

Note that in Equation (1), stability is dependent upon the negative component (*Re*) of the frequency response function (FRF) [16]. The FRF of the HRDF was measured at the bit and the results are shown in Figures 4-7.

It is clear from Figures 4-7 that the HRDF has a primary mode at approximately 5.6Hz, a secondary mode at approximately 63Hz along with other minor modes. The data in these plots were used to plot the stability diagram shown in Figure 10.

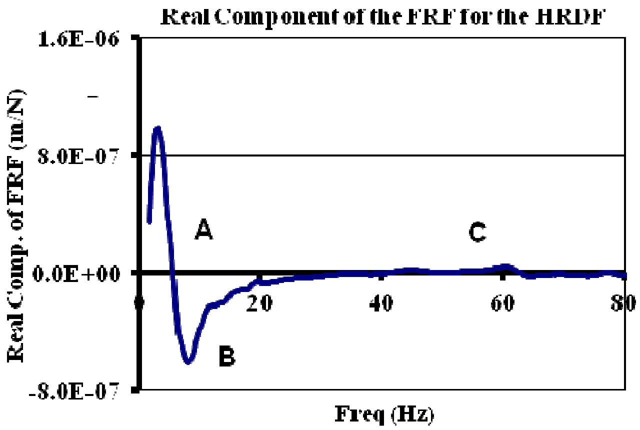

Figure 4. Real Component of the FRF for the HRDF

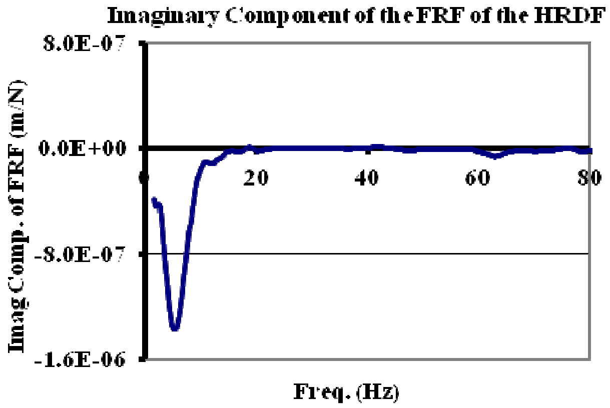

Figure 5. Imaginary Component of the FRF for the HRDF

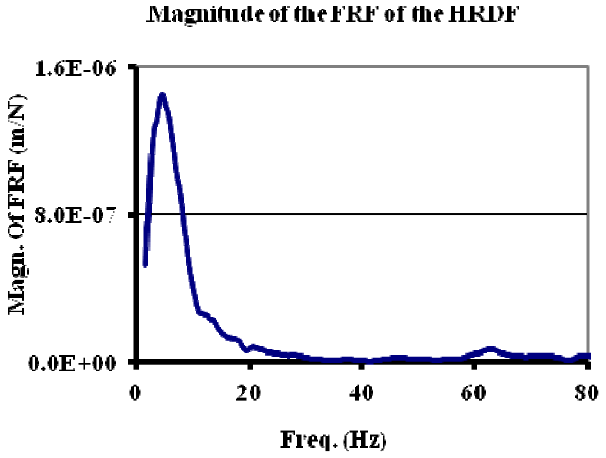

Figure 6. Magnitude of the FRF for the HRDF

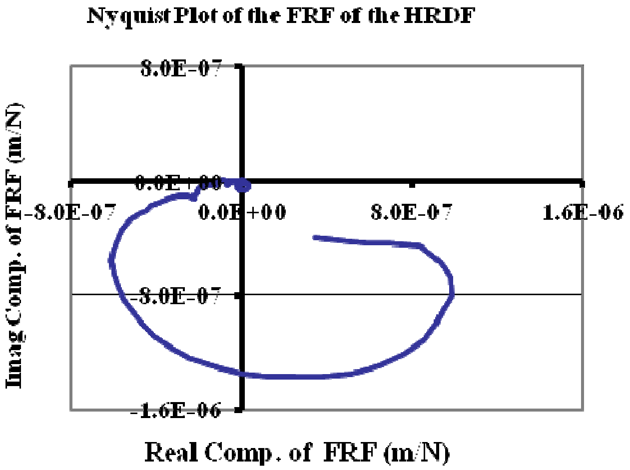

Figure 7. Nyquist Plot of the FRF for the HRDF

HRDF Model

In order to show bit displacement and force profile in the stable, unstable and quasi-stable regions, the HRDF needs to be modeled. The measured FRF of the HRDF is shown in Figures 4-7. As can be seen from Equation (1), stability is primarily influenced by the negative portion of the real component of the FRF. Therefore, any modeling of the HRDF must preserve that portion of the FRF as much as possible. Previous modeling attempts involved a trial-and-error procedure intended to represent the HRDF with a single-degree-of-freedom (SDOF) system that matched the negative component of the FRF as much as possible [16]. This approach has several drawbacks, namely:

- The HRDF is a complex system. Even though the FRF plots in Figures 4-7 show one dominant mode, other modes are still present and have an effect on drilling, particularly at high speed.
- An SDOF system is typically utilized to model bit vibrations. This is accomplished by attaching a model of the bit to the mass and following its temporal history as it interacts with the rock. Since the SDOF model is a rough estimate of the system, bit movement will also be a rough estimate, resulting in a poor representation of the rock surface.
- Realizing that small variations in bit movement can push the system from the stable to the unstable regions of the stability diagram, their effect on surface topology will be greatly exaggerated.

For the reasons noted above, the authors proposed the use of the measured FRF to obtain a more accurate MDOF (multiple degrees of freedom) model representation of the

HRDF. This was accomplished as follows:

A) Use the measured FRF in a parameter identification algorithm to obtain a MDOF model that best fits the measured FRF. Estimate model parameters using the iterative prediction-error minimization (PEM) method. The state-space equations of the model take the form:

$$\frac{dx}{dt} = A\,x(t) + B\,u(t)$$

$$y(t) = C\,x(t) + D\,u(t) \qquad (3)$$

B) It was found that a fourth-order system produces the best fit of the FRF input data. The resulting system parameters are:

$$A = \begin{array}{c|cccc} & X1 & X2 & X3 & X4 \\ X1 & -14.65 & -72.138 & 42.706 & -32.896 \\ X2 & 13.959 & -31.108 & 195.71 & -94.907 \\ X3 & -4.406 & -12.305 & -176.92 & 492.76 \\ X4 & 12.8 & 44.446 & -370.13 & -131.23 \end{array}$$

$$B = \begin{array}{c|c} & U1 \\ X1 & -4.600e-6 \\ X2 & 2.853e-6 \\ X3 & 2.089e-7 \\ X4 & 6.956e-7 \end{array}$$

$$C = \begin{array}{c|cccc} & X1 & X2 & X3 & X4 \\ Y1 & -4.152 & -8.778 & 15.540 & -9.797 \end{array}$$

$$D = \begin{array}{c|c} & u1 \\ Y1 & 0 \end{array} \qquad (4)$$

The transfer function (TF) in the Laplace Domain was found to be:

$$\frac{-9.511e-6\ s^3 + 1.338e-3\ s^2 - 0.692\ s + 306.6}{2\ s^4 + 353.9\ s^3 + 2.204e5\ s^2 + 6.944e6\ s + 3.039e8} \qquad (5)$$

C) Using the estimated model, a comparison of the FRF plots is shown in Figures 8 and 9. Notice the similarity between measured and estimated FRF of the HRDF. Notice also that the minimum value of the real component of the FRF is higher than that of the measured one. This will lead to a higher envelope of the stability diagram, as can be seen from Equation (1). However, since the point of interest here was rock surface topology, it was the overall dynamic similarities between the systems that mattered, considering that drilling rarely takes place near the limit of stability.

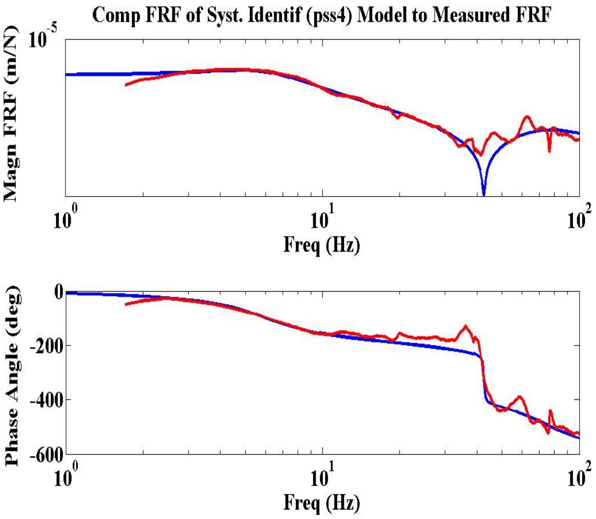

Figure 8. Comparison of Bode Plots of the Estimated Model in Equation (5) to that Measured from the HRDF

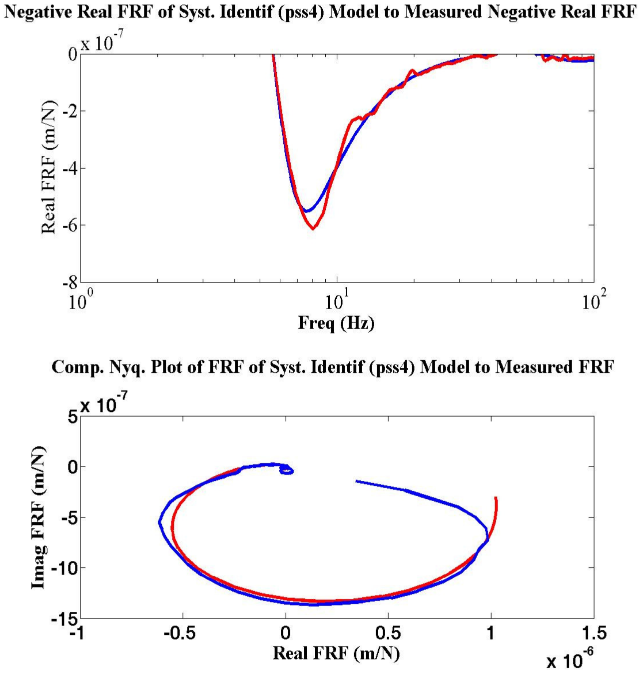

Figure 9. Comparison of the Real Components and Nyquist Plots of the Estimated and Measured FRF

Stability Diagram

To plot the stability diagram, the following steps were followed and used to produce the stability diagram shown in Figure 10 for Sandstone:

1) Pick a frequency (*f*) starting with the natural fre-

quency at point (A) of Figure 4 and proceed on the FRF curve along the A-B-C path.

2) Find real and imaginary components *Re*(*G*) and *Im* (*G*) of the FRF at the chosen frequency.

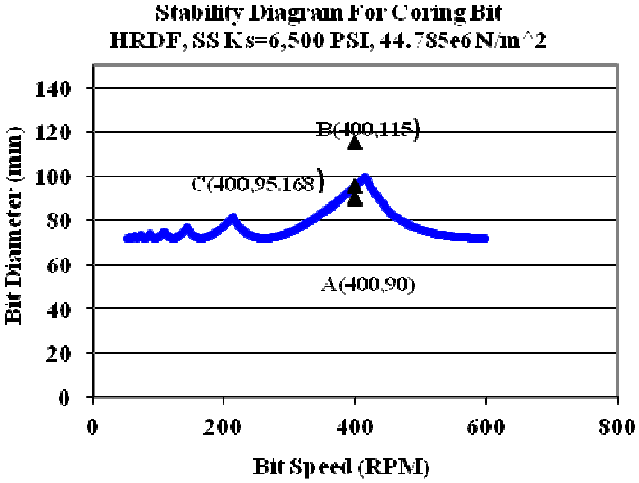

Figure 10. Stability Diagram for the HRDF with Coring Bit in Sandstone

3. Calculate the phase angle between bit force and displacement (φ) from the equation:

$$\varphi = Tan^{-1}\frac{Im(G)}{Re(G)} \tag{6}$$

4. Calculate bit diameter at the limit of stability, $d_{lim} = 2r_i + 2\, b_{lim}$ using Equation (1) for b_{lim} .
5. Calculate (ε) from:

$$\varepsilon = 180+2(180- \varphi) \tag{7}$$

6. Assuming *N*=0 for lobe (0) of the stability diagram, calculate *n* (rev/s) from Equation (2), where bit rpm=60*n*.
7. Repeat steps 1-6 for various frequencies and plot d_{lim} versus bit rpm for lobe number (0).
8. Increment *N* by 1 and repeat steps 1-7 to plot lobe (1) of the stability diagram.
9. Repeat the entire process for various values of *N* to plot the desired number of lobes of the stability diagram.

It is clear from Figure 10 that the coring bit, whose diameter was 83.26mm was stable in Sandstone in a pocket of stability at 416 RPM. At 400 RPM, the bit diameter at the limit of stability (point C) was 95.2mm. In the following section, the estimated model of the HRDF was used to plot the time histories of the bit force and displacement at points in the stable (point A) and unstable (point B) regions as well as at the limit of stability (point C). The displacement histories were then utilized to produce corresponding rock surface topologies created by bit action against the rock.

Simulation of Bit Vibration

The time history of the bit force and displacement were obtained using a numerical algorithm briefly summarized below:

A) Apply an initial force to the bit equal to the weight on bit (WOB). For the standard bit, whose outside diameter is 83.26mm, the WOB represents an initial force *F(0)* of 1500Lb. This is equivalent to a bite of

$$hav = \frac{2(WOB)}{K_s(DO-DI)} \tag{8}$$

where *DO* and *DI* are the bit's outside and inside diameters, respectively. It is worth noting that Equation (8) follows directly from the definition of the rock's Specific Power K_s.

B) To find bit displacement after an increment of time (*dt*), the estimated model in the previous section was used. With reference to Figure 11, the bit response to an initial force *F(0)* of duration *dt* is given by:

$$X(dt)= h(dt)F(0)dt \tag{9}$$

where *h(t)* is the Impulse Response Function (IRF) of the system, assuming zero initial conditions.

An incremental time (*dt*) corresponding to, say, 1 degree of rotation (*dθ*) was assumed. Using the axial position of the bit *X(dt)* as determined after the first time increment and the bit's angular rotation (*dθ*), the location of the bit (and its cutters) was known in three-dimensional space. This location, in relation to the rock surface, determines the next bite of the cutters, which in turn determines the next bit force *F(dt)*. Using the response *X(dt)* as the initial condition for the next *dt*, the response *X (2dt)* was obtained. The bit force *F(2dt)* was again used to find bit displacement after another (*dθ*) degrees of rotation and the process was repeated.

C) This algorithm produces the time histories of bit force and displacement. The final shape of the rock surface after a desired simulation time interval revealed the surface topology.

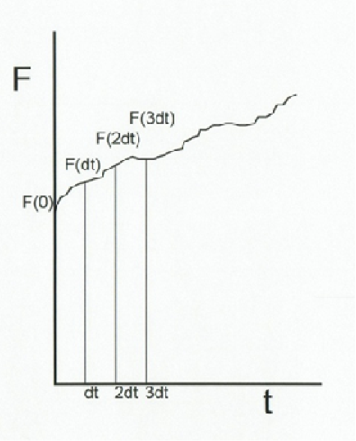

Figure 11. Schematic of the Bit Force

Results and Discussion

The procedure outlined above was used to model bit behavior at 400 RPM in three cases: stable drilling at a bit diameter of 90mm (point A in Figure 10), unstable drilling at a bit diameter of 115mm (point B in Figure 10) and at the limit of stability for a bit diameter of 95.2mm (point C of Figure 10). For each point, bit displacement, force and rock surface topology were obtained 5 seconds into the simulation. All bits contained three cutters located at 0°, 155° and 246° angles as explained in the previous section. The stable bit with 90mm OD had the 26.82mm diameter cutters. For other bits with 115mm and 95.2mm OD, the cutter diameter was scaled up by the ratio of *DO-DI* such that:

$$\text{Cutter OD (mm)} = 26.82\ (DO\text{-}DI)/(83.26\text{-}31.04) \qquad (10)$$

Moreover, the weight on bit for the 83.26mm bit was 1,500Lb (6,682N) with the value for other bits given by:

$$\text{WOB (Lb)} = 1500\ ((DO\text{-}DI)\ /\ (83.26\text{-}31.04) \qquad (11)$$

In effect, the force per unit length of the bit cutting profile was preserved. The rock used in the simulation was Sandstone, whose K_s was 6,500psi. The results are given below:

Bit Force

The bit force in the three cases outlined above is plotted against time in Figures 12-14. From Figures 12-14 it can be seen that the force on the stable bit settles down to a value corresponding to the weight on bit (WOB). However, for the unstable bit in Figure 13, the force increases with time but is self-limiting. This phenomenon occurs due to the fact that excessive vibration causes the bit to bounce above the rock surface, thereby relieving the bit force. This can be seen in Figure 13 where the bit force becomes zero once every cycle after a short period of drilling. This situation is referred to as saturation.

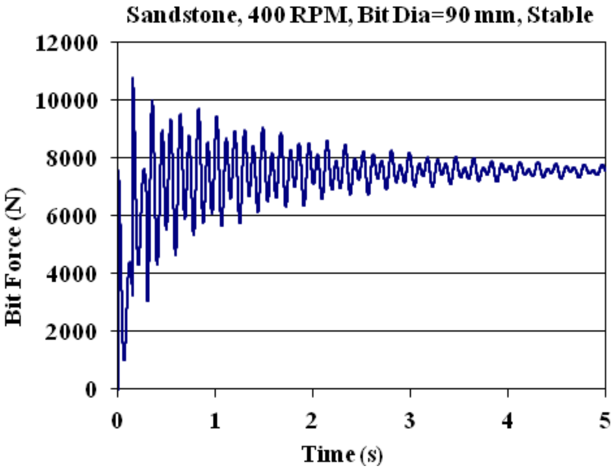

Figure 12. Bit Force in Stable Drilling, Point A of Figure 10

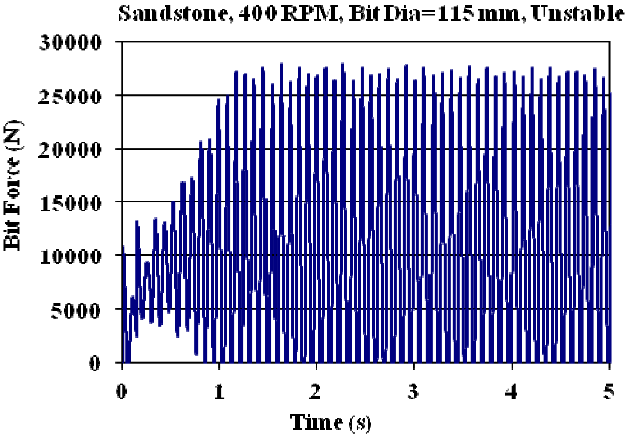

Figure 13. Bit Force in Unstable Drilling, Point B of Figure 10

The force profile at the stability limit in Figure 14 shows that vibration amplitude remains unchanged over time after the initial transient, as would be expected from a quasi-stable system.

Bit Displacement

The corresponding bit displacements are shown in Figures 15-17.

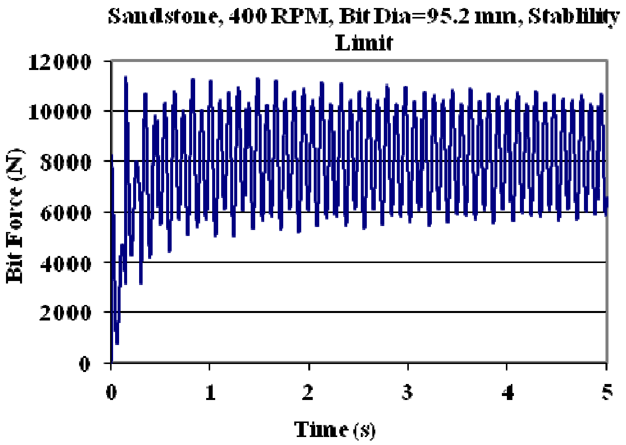

Figure 14. Bit Force at the Limit of Stability, Point C of Figure 10

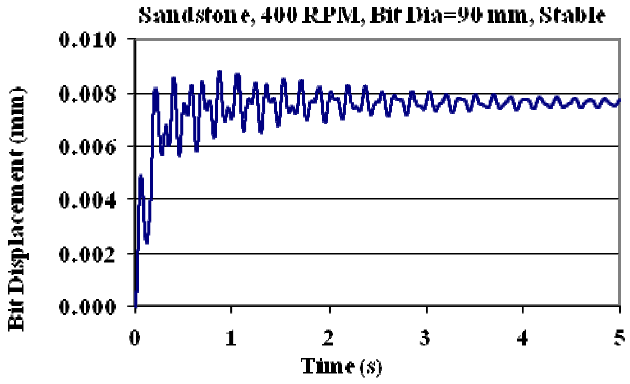

Figure 15. Bit Displacement in Stable Drilling, Point A of Figure 10

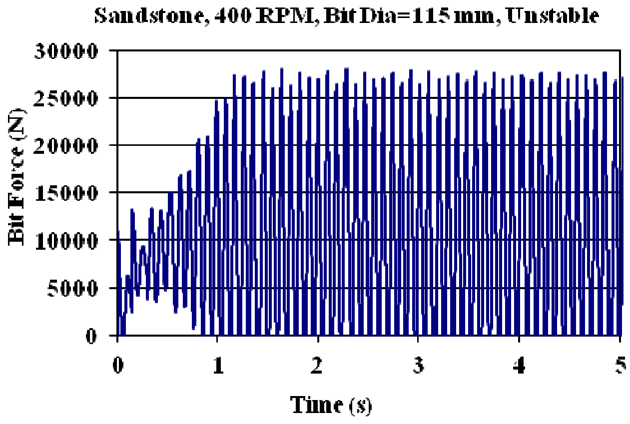

Figure 16. Bit Displacement in Unstable Drilling, Point B of Figure 10

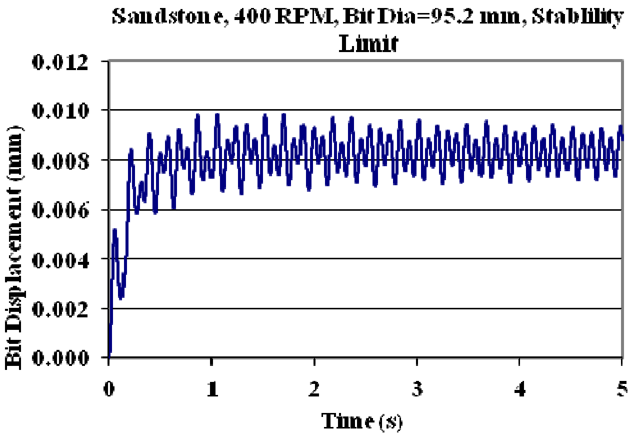

Figure 17. Bit Displacement at the Limit of Stability, Point C of Figure 10

Again, note the saturation phenomenon which limits bit displacement for the unstable system of Figure 16 and that the average bit displacement of Figure 15 corresponds to the bite taken by the bit under the static load represented by the corresponding WOB.

Rock Surface Topology

Rock surface topologies obtained from the simulation are shown in Figures 18-20. From Figures 18-20 it can be seen that the smooth rock surfaces generated in stable and quasi-stable drilling contrast the erratic appearance of rock surfaces in unstable drilling (Figure 19). For comparison, typical rock surfaces obtained from testing on the HRDF drilling in Sandstone are shown. Figure 21 shows surface topology in stable drilling while Figure 22 shows the topology in unstable drilling. Here again, one can see that there are similarities between these surfaces and the corresponding surfaces obtained through simulation. Severe chatter in unstable drilling causes cutter breakage due to destructive impact loading. A typical broken cutter is shown in Figure 23.

Summary

In this paper, it was shown that measurement of the FRF of a drilling rig can be utilized for the purpose of analyzing its stability in rock drilling. The resulting stability diagram was used to establish combinations of bit diameter and speed where drilling is stable. Moreover, utilizing the FRF, the severity of vibrations in drill bits can be predicted. Time simulation was utilized to show bit displacement and forces as well as rock surface topology in the stable, unstable and quasi-stable regions of the stability diagram.

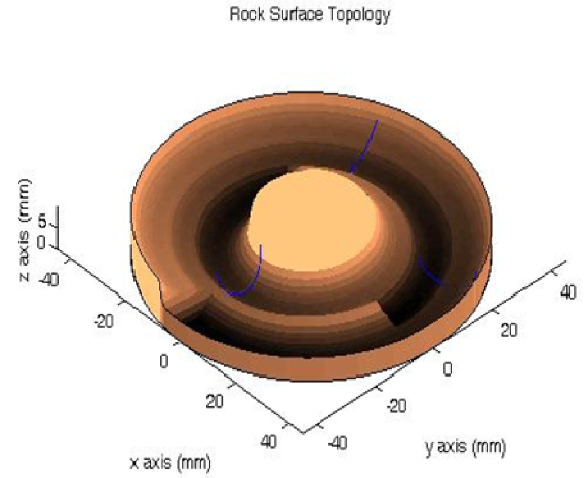

Figure 18. Rock Surface Topology in Stable Drilling, Point A of Figure 10

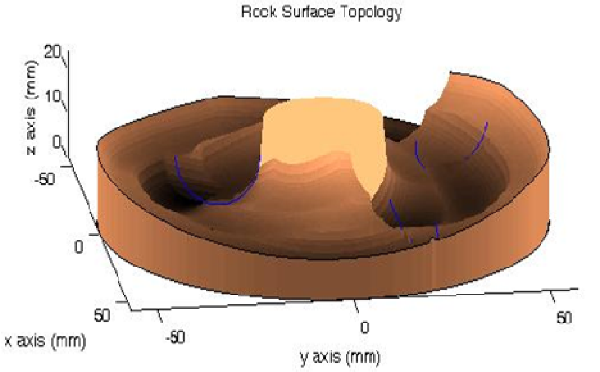

Figure 19. Rock Surface Topology in Unstable Drilling, Point B of Figure 10

It was also shown that the erratic bit behavior for an unstable system is reflected in rock surface topology. Laboratory tests showed similarities in rock surface appearance and, in the case of unstable drilling, led to failure of the PDC cutters.

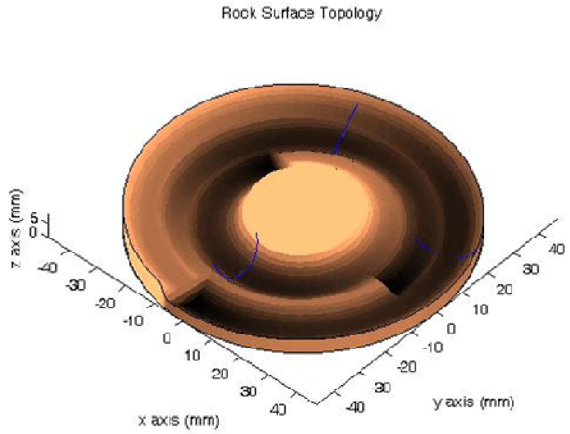

Figure 20. Rock Surface Topology at the Limit of Stability, Point C of Figure 10

Figure 21. Typical Rock Surface Topology in Stable Drilling

Figure 22. Typical Rock Surface Topology in Unstable Drilling

Figure 23. Typical Broken Cutter in Unstable Drilling

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Biography

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TEST BATTERY FOR EVALUATION OF TASK PERFORMANCE AND SITUATIONAL AWARENESS

Reza Karim, North Dakota State University; Kambiz Farahmand, North Dakota State University

Abstract

In this study, a test instrument was developed to measure human cognitive task-performance capacity and situational awareness. Task capacity of a subject was measured before and after doing a low level of physical exercise. Signal-detection theory was applied to find the situational awareness of individuals in the form of true-or-false responses. The tool compares the task capacity among different age and sex groups. The effect of low-level stress on performance due to physical exercise was determined, and a relationship was established between cognitive task and situational awareness. Response Time, accuracy and repeatability were measured for statistical analysis. It compared pre- and post-stress effects on task performance. A stress level of the subject was measured using a questionnaire before participating on the test. The Delphi method was used to find the consensus on the test designed. The task capacity and situational awareness were expected to vary due to the effect of physical stress. Preliminary results indicated that average accuracy of selecting the correct answer was 84% and the average time taken to complete the test was 15.9 minutes. Also, 81.4% of the task-capacity-related tasks and 89.9% of the situational-awareness-related tasks were correct in Phase I of the experiment.

Introduction

Human perception, cognition and action takes place in a sequential manner; input is sensed and then processed, followed by an output [1]. All current information on how the human mind works is based on this principle. Task capacity has been studied in many areas. Task-capacity studies in Psychology or Clinical Psychology investigated relationships to mental disease. Neuroscience research evaluates the physical capability of the human brain. Human capacity can be classified into physical ability and task capacity. There are many ways to measure physical ability such as strength, oxygen consumption and heart rate. On the other hand, situational awareness is the foundation of decision making. Task capacity is a complex process; there are many questions to answer on how to standardize and measure task capacity and situational awareness.

The rapid advancement of technology and the increased complexity of work forces operators to adapt their decision-making process in a dynamic environment. Workload is defined as the physical and mental requirements associated with a task. The proportion of physical load and mental load varies with the task types. Workload as a function of task requirement places demands on the human subject. The capacity of the subject is challenged to perform the workload. If the workload is higher than the operator capacity, the subject feels overloaded. A dynamic decision-making process is considered as a real-time decision maker, which is constrained by the decision-making environment [2]. Plane and car accidents occur most often due to stresses on the operators of those vehicles. Stress, exceeding the tolerable limit, can be caused by physical conditions, physiological conditions or mental conditions. Environmental conditions and task loads develop stress not only in normal environmental conditions, but also in any type of confined environment. To find an appropriate person for a task, the assessment of task load and the impact it creates in performing the task is very important.

Background

Cognitive abilities play a key role in the adequate management of workload by individuals performing complex tasks [3]. Workload is dependent on task demand and varies with the capacity of the subject to meet those demands [4]. Studies show a decrement in performance as workload decreases [5]. A sudden decrease or increase of workload leads to a loss of accuracy and slows response time in a longer work period. Experimental studies on cognitive performance usually keep workload constant.

Not much attention has been paid in recent years to the relationship between task demand and cognitive abilities of the subject performing the task. Some studies examined the effect of physiological activities on cognitive tasks. In the case of a short duration of physical activities, a decrease of accuracy in performing cognitive tasks was observed, such as in the case of map interpretation [6]. Some findings indicate reverse results in arithmetic task performance at an intermediate level of physical task [7].

The need of a standard process describing and measuring task performance has well been recognized. Putting the right person on the job is a tremendous challenge for companies.

The tasks performed in any manufacturing facility are routine and repetitive; efficiency and quality require standardized work procedures [8]. The standard process requires being able to measure the effect of stress on cognitive task performance with greater degree of accuracy. Task performance capacity and physical performance capability vary from person to person [9]. These two conditions are independent of each other. For example, a basketball player may be very good in physical activities but may not be as good in cognitive tasks. There are different mechanisms developed to measure physical abilities [10]. Not many methods are developed to measure cognitive task performance to find the stress effect. There is a challenge to develop an appropriate method and tool to simultaneously measure Cognitive Capability (CC) and Situational Awareness (SA) quickly and effectively.

Poor performance can occur using less-friendly devices and could cause catastrophic error. Buckle [11] outlined the design challenges in the healthcare sector. The author provided some approaches and methods that allow ergonomists to design any systems. Use of these design approaches was helpful to reduce the probability of medication error. Silver [12] studied the process carried out by the providers to improve the quality of the service provided based on the human-factors approach. The key design considerations included task information characteristics, task allocation, redundancies, and the competing goals of the operator. Spear [13] studied the ergonomics issues arising in the emergency department. The quality of healthcare service was improved by reducing the physical stress induced in the staff and patients due to the physical layout of the machines and equipment in a facility.

The Delphi method is generally used to develop the test procedure by consulting the experts in the specific field of application of the test battery. The test tasks and sequence of tasks are developed from expert opinion to fit the test objectives. The method standardizes the procedure to conduct the task-capacity test. Goodman [14] compared the Delphi approach with the committee-decision approach. The Delphi method was chosen when the problem benefits from subjective statements made under a collective basis. Information was collected based on anonymity. Interpersonal interaction was eliminated to avoid the controlling variables in decision making. The key characteristics of the Delphi method, anonymity, use of experts and controlled feedback, were examined in the Delphi study. Anonymity has advantages because it helps the participants to state their true opinion without being influenced by peer pressure. The disadvantage of the Delphi method is lack of accountability.

On the other hand, since the panel is selected on the basis of their knowledge and willingness to participate, the accountability problem may not be an issue. The validity of the study depends on the selection of experts instead of a random sample. Hasson [15] conducted methodological issues in nursing research, such as preparation, action steps and difficulties that are inherent within the Delphi technique. The validity of this method was enhanced by reasoned argument in which assumptions were challenged. Findings from the Delphi study help streamline work. Three issues guide data collection: the discovery of opinion, the process of determining the most important issues and managing opinions-data analysis. The verbal approach, combined with the written approach, was found to be more effective in the Delphi method. McKenna [16] described the Delphi technique and criteria for selecting it as a research tool. The Delphi method used for systematic collection and aggregation of information provided by the group of experts on specific questions and issues related to the subject of concern.

The research population covers a diverse background in experience or expertise. If there is a lack of empirical data, Delphi is appropriate. The unique aspect of this method is convergence towards agreement. It helps in developing knowledge and policy of a particular problem. Because of grassroots' involvement, the results from Delphi activities are widely accepted. Powell [17] emphasized the need for the development of scientific merit questions. Individual judgments recorded and combined in addressing the issues. The first-round questionnaire was unstructured and obtains open responses, allows participants to elaborate on the topic, and a qualitative analysis of the results allows constructing the second and subsequent questionnaires.

The diversity of viewpoints that develops controversy helps to generate interest and involvement among the selected experts. A heterogeneous group produces more high-quality acceptable solutions than a homogeneous group. Villiers [18] described different types of Delphi techniques: conventional and real time. In the conventional method, a questionnaire is first sent to a group of experts; in the second round, a questionnaire is sent back to the experts based on the result from the first round. The third round is used depending on the consensus level from previous rounds. In the real-time technique, the process takes place using a meeting where a summary of the responses of the respondent is made immediately. The decision maker obtains information on options with supporting evidence from the forum and makes the decision. The forum does not make the decision.

Methodology

The test methodology developed here measures human cognitive task performance capacity and situational awareness simultaneously and compares task capacity among different age and sex groups. Cognitive task capacity and situational awareness of a subject is measured before and after doing a low level of physical exercise. Signal-Detection theory is applied to find the cognitive task capacity and situational awareness of individuals in stressful conditions in the form of true-or-false responses while measuring the confidence level of selecting the appropriate answer. Cognitive task-capacity measures differ among the groups based on stress level of the subject. Task performance is measured in two stages. Low-level physical work is set for the participant after the first stage. The tool determines if stress has any effect on the task performance. The test methodology determines any relationship between task performance and individual SA. Response Time, accuracy, and repeatability of performing a given task are recorded for statistical analysis to justify the findings. A questionnaire developed through a Delphi study was used to measure the level of stress experienced by the subject participating in the test before hand. This pre-test creates a baseline of the candidate's stress level. If it is determined that the subject is stressed, the test will be rescheduled. The research focused on determining the following:

1. Develop the Task Capacity Model using performance parameters described by Miller [24]. Microsoft Visual C# 2.0 program in Microsoft.Net 2.0 platform to construct the model.
2. Standardize the Test using Delphi Techniques
3. Measure Task Capacity and Situational Awareness simultaneously using Signal Detection Theory
4. Determine dual task performance capacity
5. Objective queries and subjective self-ratings of confidence for each response determined
6. Determine any effect of low level stress on task performance

The focus of this research was to develop a standardized task-capacity model. Human-factor issues are considered to measure CC and SA simultaneously and to determine whether there is any effect of physical stress. Task complexity can be altered by changing the number of elements of a task. Task complexity affects attention, accuracy and repeatability of a task. The task-capacity model considers a standard task-performance procedure created using the Delphi technique.

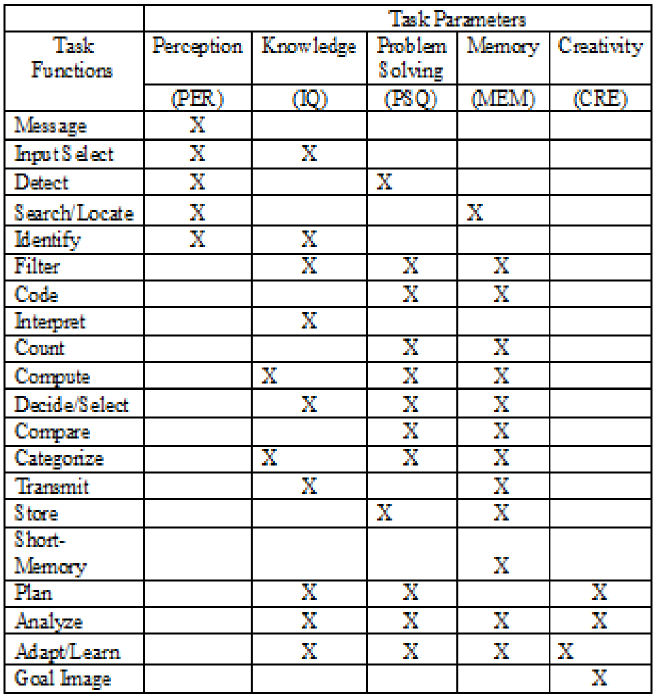
Mental capacity is the potential to understand and follow the general logic of real-world tasks from the user's perception. Mental capacity combines two characteristics of the brain; one is the capacity to store and recall information (memory capacity) and the other is the capacity to perform logic-processing operations (problem-solving capacity). Problem-solving capacity and knowledge are independent measures of task capacity. But a high level of knowledge can enhance problem-solving efficiency. The General Aptitude Test Battery (GATB) and the Employment National Job Service Committee (ENJSC) have been used in the United States for hiring people and to improve relationships between employers and employees. The GATB has been described as having shortcomings by many authors [19]. Time given for the test is also a concern. IQ, SAT, ACT, academic records, GPA or work experience are considered for hiring people. Problem-solving capacity and behavioral characteristics are not considered in many test methods.

Situational awareness is defined as the ability to identify the desired elements from the environment, process information and combine the critical elements of the information on the current situation. SA measures one's ability to recognize the present scenario and predict the future state of the gathered information. Performance parameters in a complex task model are dependent on SA. For example, in a flexible manufacturing system, operators must have up-to-date knowledge on machine-tool parameters as well as the functioning for future process-state changes [20]. Military personnel frequently rely on SA to make decisions on the battle field [21]. Inaccurate or incomplete SA could cause loss of life or unnecessary expenditure of resources. In recent years, the military has employed increasingly sophisticated equipment on the battle field, which requires portable computing operations. The solders are required to be able to perform simultaneous, cognitively demanding information-processing tasks and physical tasks. Many studies show that high SA scores support good task performance. Stress may affect SA through a decrease in working memory capacity and retrieval [22]. A preview of the literature suggests [23] that sensory tasks are enhanced by all levels of physical activities. It can also be seen that improvement of memory and information processing by physical exercise.

Performance Parameters

Five performance parameters representing the real-world tasks were described by Miller [24], as shown in Table 1. The twenty task functions are used to establish the relationship between task functions and task-performance parameters. From the relationships between task functions and test parameters [24], the scoring technique is obtained. Equal brain capacity is assumed for each task.

Table 1. Relationship of Task Functions and Task Parameters



	Task Parameters				
Task Functions	Perception	Knowledge	Problem Solving	Memory	Creativity
	(PER)	(IQ)	(PSQ)	(MEM)	(CRE)
Message	X				
Input Select	X	X			
Detect	X		X		
Search/Locate	X			X	
Identify	X	X			
Filter		X	X	X	
Code			X	X	
Interpret		X			
Count			X	X	
Compute		X	X	X	
Decide/Select		X	X	X	
Compare			X	X	
Categorize		X	X	X	
Transmit		X		X	
Store			X	X	
Short-Memory				X	
Plan		X	X		X
Analyze		X	X	X	X
Adapt/Learn		X	X	X	X
Goal Image					X

Test Instrument

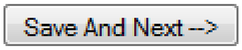
The test was designed to cover human task capacity and situational awareness in the following areas: computation, dual task, three-dimensional review, vocabulary, pattern recognition, comparison and arithmetic reasoning.

This study was broken into two phases, performed sequentially. The time gap between two tests is at least one week. Phase I was conducted to determine task capacity and situational awareness simultaneously with a set of tasks in the form of questions. Phase II compared stress produced by the physical activity performed right before participating in the experiment. There was one experimental trial for each subject in Phase I. Each experimental trial consisted of thirty tests in random order. Similarly, Phase II consisted of one experimental trial with thirty tests in random order. Phase II followed after fifteen minutes of light physical work at a set room air temperature and relative humidity. Subjects answered six stress-level measurement questions before and after the tests. Approximately sixteen subjects were desired to complete the two phases of the experiment. Ages ranged from twenty-one to forty. The selection process was random; anyone who was physically fit could participate in the test. An individual approach was conducted to recruit subjects.

This sample size provides a statistical power [25], 1-β, of 0.95 when using an analysis of variance to compare mean task capacity of at least eight individuals participating in the experiment, assuming the study detects task-capacity differences of 15% between Phase I and Phase II with a standard deviation of 7. The goal was to have a balanced experimental design for subsequent statistical analysis. It was desired that the same eight subjects participate in both experimental phases. However, if subjects could not continue after completion of Phase I, they would not be replaced by other participants during Phase II.

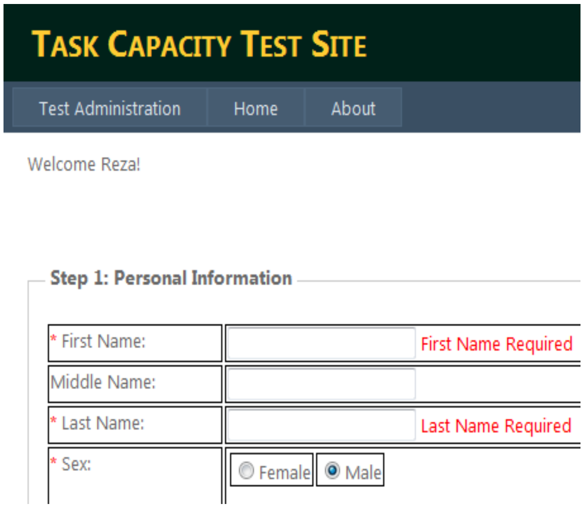
The test scenario was constructed using Delphi techniques. Test specifications used were: Measure of Response Time (RT), Accuracy (AC) and Repeatability (RP). Cognitive capacity was measured in terms of IQ, MEM and PSQ. Situational Awareness (SA) was measured by describing a situation and after a set time period, situational-related questions and scenarios were presented to the subject. Human-factor issues were considered when designing the test setup. The test was computer generated. Computer tables and chairs were positioned to allow the participants to adjust the height to their comfort level. All personal information was stored in the database with a unique user-identification number. This was necessary because the same participant was expected to appear in Phase II of the experiment. The total number of participants considered for the test was ten. The same participants appeared in Phase I and Phase II. Phase II was conducted after the participants performed a physical task for a specified amount of time to simulate stress.

This section describes the tool developed for data collection. A Battery-test link was put on the desktop to enter into the program. Login information was provided to the subject to enter onto the site. Personal information was recorded in the first section. Part of the tool is shown in Figure 1. After completion of the personal information, a stress-level determination question was asked (see Figure 2). After the STRESS input, the test would start by pressing



The approximate time of the test was fifteen minutes. The following section provides an example of how the test scenario was designed.

The subject checks the appropriate button by comparing possible answers with the given answer. Right after selecting YES/NO, the subject selects a confidence level that describes how confident he/she is on selecting the answer. After completion of each question, the subject presses the submit button and goes to the next level.

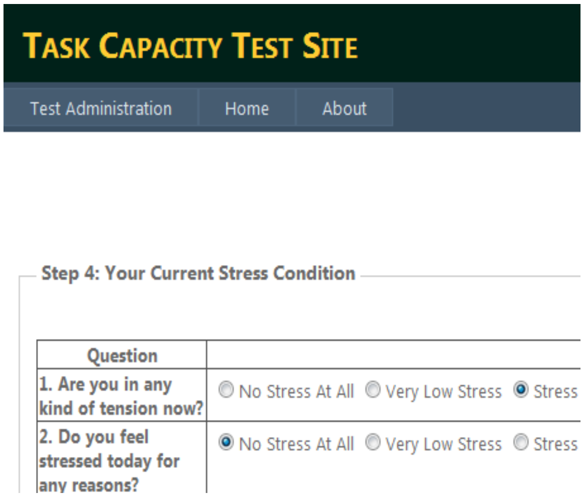


Welcome Reza!

Step 1: Personal Information

* First Name:		First Name Required
Middle Name:		
* Last Name:		Last Name Required
* Sex:	○ Female ● Male	

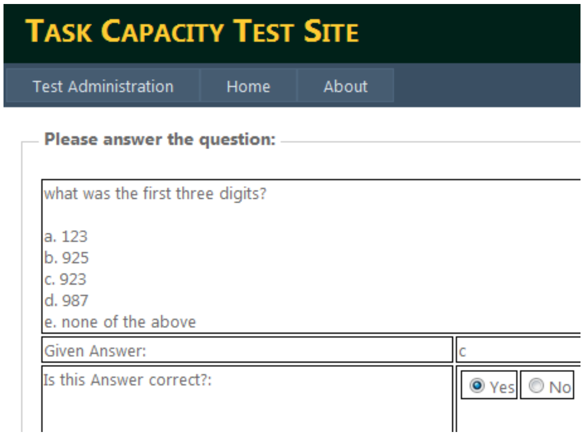
Figure 1. Snapshot of the Personal Information Collection Tool



Step 4: Your Current Stress Condition

Question	
1. Are you in any kind of tension now?	○ No Stress At All ○ Very Low Stress ● Stress
2. Do you feel stressed today for any reasons?	● No Stress At All ○ Very Low Stress ○ Stress

Figure 2. Snapshot of the Stress Measurement Tool



Please answer the question:

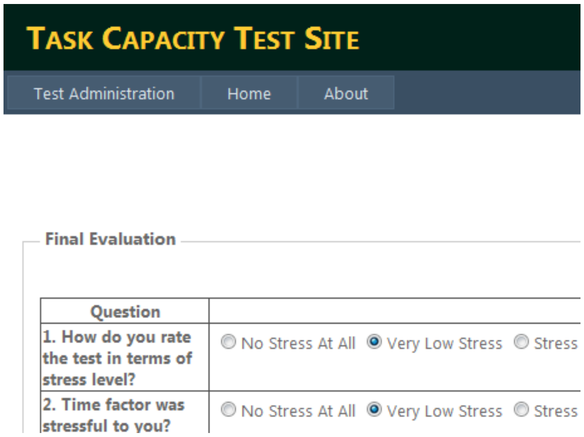
what was the first three digits?

a. 123
b. 925
c. 923
d. 987
e. none of the above

Given Answer:	c
Is this Answer correct?:	● Yes ○ No

Figure 3. Snapshot of a Questionnaire Tool

After a successful completion of the test, a STRESS-level measurement question would appear. The subject needed to select the appropriate level that described his/her stress level. After finishing the stress test, the subject presses the Save-and-Finish Test button to complete the test.



Final Evaluation

Question	
1. How do you rate the test in terms of stress level?	○ No Stress At All ● Very Low Stress ○ Stress
2. Time factor was stressful to you?	○ No Stress At All ● Very Low Stress ○ Stress

Figure 4. Snapshot of Stress Measurement Tool

Discussion & Results

Sample data were collected to verify the tool. Eight people were invited to participate in Phase I, and five responses were obtained. Table 2 shows a sample of data collected for a subject.

Table 2. A Sample Representation of the Data Collected for Each Subject

Questions	Correct Ans.	Given Ans.	User Ans.	Is User Correct	Confidence Level	Response Time(ms)	Movement Time(ms)
1. Which pair of name is the same?	A	B	No	Yes	Very High	30265	3022
2. Add (+): 766 and 11	E	A	No	Yes	Very High	16786	1617

Table 3 summarizes Response Time, cursor movement time and accuracy of the responses for each subject.

Table 3. Response Time and Accuracy

	Phase I		
ID	Response Time (RT) in seconds	Cursor Movement Time (RT) in seconds	Accuracy (AC) (%)
01	419.79	366.70	85
02	1018.13	434.42	90
03	1504.24	679.99	80
04	918.02	116.56	90
05	915.04	535.47	75

Table 4 represents task capacity and situational awareness measured in percentage. There are fourteen task-capacity tasks and six situational-awareness measurement tasks considered for the test.

Table 4. Task Capacity and Situation Awareness

Phase I		
ID	Task Capacity (%)	Situational Awareness (%)
01	78.6	100
02	85.7	100
03	71.4	100
04	92.86	83.33
05	78.57	66.66

It was observed from the data that subjects make incorrect selections even at high-confidence levels. The participants made 89.9% correct selections for the situational-awareness tasks.

Conclusion

The current research focused on standardizing the task functions to measure individual task capacity. The Delphi method, which is usually applied in social policy and public health, was considered as a research tool to determine the needs and skills required in any specific work environment. Using a single tool simultaneously to measure cognitive task capacity and situational awareness was expected to be a useful application in the dynamic and complex work environment of manufacturing industries. Low-level stress becomes a challenge on cognitive task performance when repetitive tasks are performed. The method developed in this research is expected to differentiate the type of task functions that are affected significantly when stress is a concern. Self-rated stress measurement examines what type of tasks may be considered as a stressor to individuals.

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ESTIMATING π AS AN INTRODUCTION TO TECHNICAL COMPUTATION

Mark French, Purdue University

Abstract

Engineering technology students often begin their college experience with minimal training in technical computing. A simple exercise in computing an approximate value of π can introduce basic concepts and commonly used software, while calculating a familiar number. Several methods of approximation are presented here, starting with an intuitive geometric approach and progressing to more efficient methods based on series expansions. Initial presentation of this exercise in a math review class for engineering technology students was successful.

Background

Perhaps the most universally used mathematical constant, π appears in expressions across a wide range of technical fields. Every engineering technology student knows that π is approximately equal to 3.14 or 22/7. Given a dozen decimal places, it is possible to express the circumference of a circle 1 million kilometers in diameter with an accuracy of 1mm. While there is no engineering reason to need more than about a dozen decimal places, the numerical value of π is currently known to more than a trillion decimal places. There are several reasons for this incredible level of precision. One is that number theorists are looking for patterns in the series of digits, though π has been proven to be irrational and, thus, cannot terminate in a repeating series of digits no matter how long the number. Another more practical use is to verify the accuracy of new computers by showing that they can correctly calculate π to a large number of digits [1].

Engineering technology students are generally just told that π is the ratio of the circumference of a circle to its diameter and that it has a certain approximate value. Common scientific calculators have π programmed to around a dozen significant digits and some students even take it upon themselves to memorize them. However, is it very uncommon for students to be shown where the numerical value of π comes from and even more rare for them to do the actual calculation.

This situation offers an opportunity to both introduce technology students to some basic ideas about technical calculations and to remove some of the mystery surrounding this universal constant. Fortunately, several means of calculating π are well within the mathematical abilities of technology students who are not yet familiar with the basics of calculus, though a basic knowledge of calculus allows more efficient methods to be used. Many different methods have been proposed over the last few thousand years [2], [3]; what follows is a description of several representative approaches in roughly increasing order of sophistication, along with sample calculations.

Method of Polygons

Among the first known approximations of π are 25/8 (3.125) from the Babylonians and 256/81 (approximately 3.1605) from the Egyptians [4]. Both appear to date from around 1900 BC. The first known rigorous estimate was by Archimedes (287-212 BC). He showed that π can be approximated by inscribing and circumscribing regular polygons on a circle, as shown in Figure 1. As the number of sides increases, the sum of the lengths of the sides approaches the circumference of a circle. The inscribed polygon approaches the circumference of the circle from below, while the circumscribed polygon approaches from above. This method is an important one because it allows calculation to any accuracy desired by simply increasing the number of sides of the polygons.

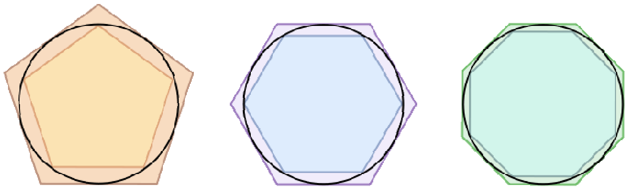
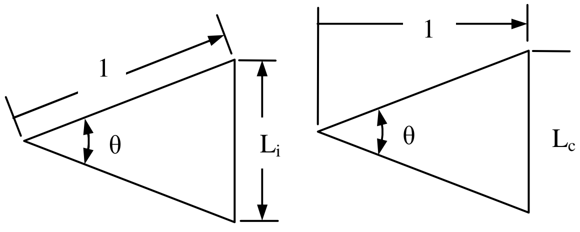


Figure 1. Archimedes' Method of Inscribed and Circumscribed Polygons (Wikipedia Commons. Image is in the public domain)

The circumference of a regular polygon with N sides is N times the length of the base of one segment, as shown in Figure 2. The geometry is slightly different for the inscribed and circumscribed triangles, though both are isosceles. For simplicity, assume the radius of the circle is 1.



Inscribed Segment

Circumscribed Segment

Figure 2. Dimensions of Polygon Segments

For the inscribed polygon with N sides,

$$\sin\left(\frac{\theta}{2}\right)=\frac{L_i}{2} \quad \Rightarrow \quad L_i = 2\sin\left(\frac{\theta}{2}\right) \qquad (1)$$

where θ = 360°/N. For the circumscribed polygon,

$$\tan\left(\frac{\theta}{2}\right)=\frac{L_c}{2} \quad \Rightarrow \quad L_c = 2\tan\left(\frac{\theta}{2}\right) \qquad (2)$$

If the radius of the circle is 1, then the circumference is 2π and

$$N\sin\left(\frac{\theta}{2}\right) \le \pi \le N\tan\left(\frac{\theta}{2}\right) \qquad (3)$$

Of course, calculating an estimate for π depends on the ability to calculate sine and tangent functions. Figure 3 shows how the upper- and lower-bound estimates converge as N increases. The average of the two estimates produces a more accurate result than either estimate individually.

Before moving to the next method, it is worth noting that Equation 3 is true even when N is not an integer. For example, choosing N=123.456 gives the estimate 3.141254 ≤ π ≤ 3.1412271. To go one step further, N does not even have to be real. For example, N = 123.456 + 89.0123i gives 3.141522 + 2.116587i $\times 10^{-4}$ ≤ π ≤ 3.141734 + 4.233687i $\times 10^{-4}$. Note that using complex arguments gives complex results whose imaginary parts are very small. As the magnitude of the complex argument increases, the imaginary part of the result approaches zero and the result is a real number. This a useful example of how an equation developed from a simple, intuitive starting point can be applied more generally than its derivation might suggest.

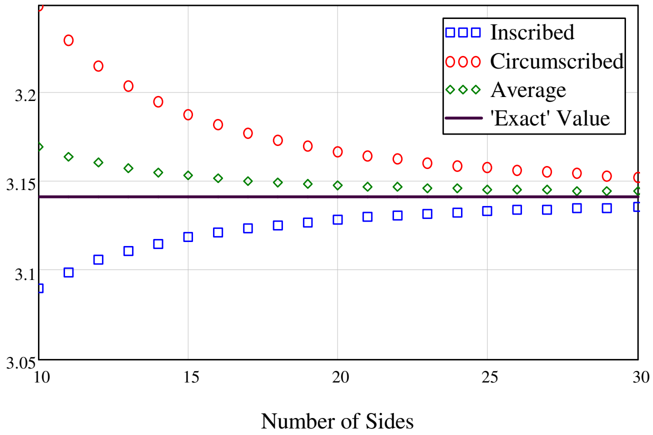


Figure 3. Convergence of Polygonal Approximations

Summation of Boxes

Another approximate method appears to have been proposed slightly before the development of calculus and will look familiar to any student who has seen a graphical explanation of integration [5]. The area of a circle is πr^2 and the equation describing a circle with a radius of 1 is $x^2+y^2=1$. It is easy in principle to approximate the area of a quarter circle by dividing it into vertical boxes (as shown in Figure 4) and simply adding up the areas of the boxes. As the number of boxes increases, the boxes' total area approaches the exact area of the quarter circle. This is essentially the definition of an integral.

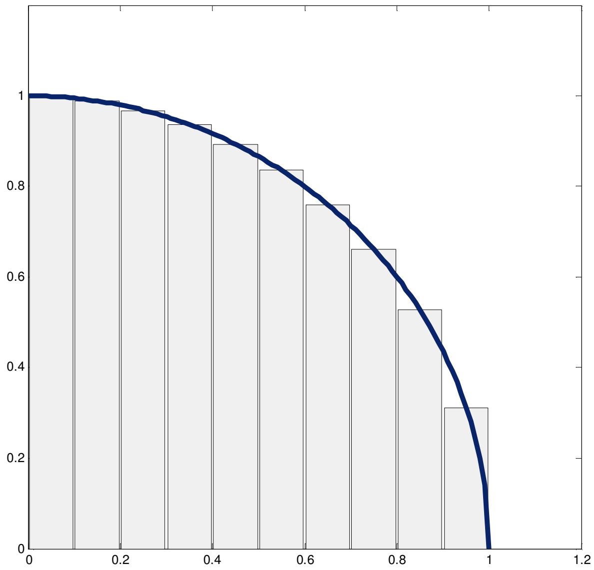


Figure 4. Summing Rectangles to Approximate Area of Quarter Circle

The expression for the area of the quarter circle is

$$A=\sum_{i=1}^{N}\sqrt{1-x_i^2}\,\Delta x=\sum_{i=1}^{N}\sqrt{1-\left[\left(i-\tfrac{1}{2}\right)\frac{1}{N}\right]^2}\,\frac{1}{N} \qquad (4)$$

Since the radius of our circle is 1, π = 4A. Figure 5 shows convergence of this expression compared to Archimedes' method. It clearly produces an accurate result faster and does so without the need to calculate trigonometric functions. However, this comes at the price of having to calculate square roots.

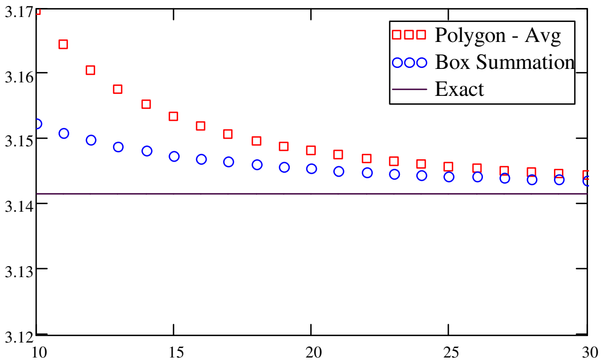


Figure 5. Convergence of Summed Rectangle Estimate

Summation of Segment Lengths

A more sophisticated approach is to sum the length of arc segments on the quarter circle as shown in Figure 6. The quarter circle can be divided into segments with equal spacing along the horizontal axis (Δx is constant). The length of any individual segment is

$$L_i=\sqrt{\Delta x_i^2+\Delta y_i^2} \qquad (5)$$

so the approximate length of the quarter circle is then

$$\frac{C}{4}=\frac{\pi r}{2}=\sum_{i=1}^{N}\sqrt{\Delta x_i^2+\Delta y_i^2} \qquad (6)$$

Since the radius of the circle is 1, Δx=1/N and x_i=i/N. Now, this expression can be re-written as

$$\begin{aligned}\pi&=2\sum_{i=1}^{N}\sqrt{(x_i-x_{i-1})^2+(y_i-y_{i-1})^2}\\&=2\sum_{i=1}^{N}\sqrt{\left(\frac{1}{N}\right)^2+\left(\sqrt{1-\left(\frac{i}{N}\right)^2}-\sqrt{1-\left(\frac{i-1}{N}\right)^2}\right)^2}\end{aligned} \qquad (7)$$

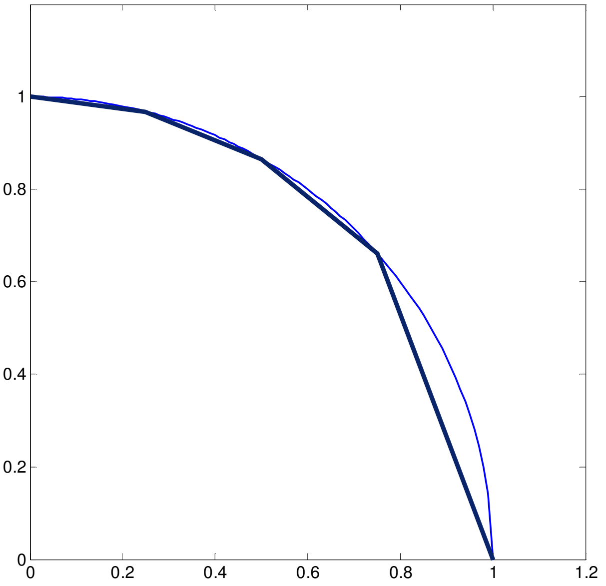


Figure 6. Defining Lengths of Segments

As N gets larger, this expression converges to π, as shown in Figure 7.

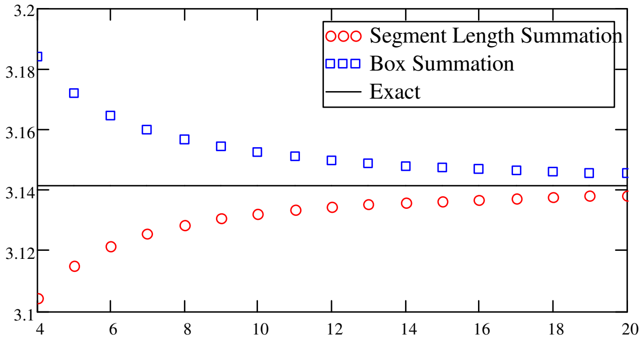
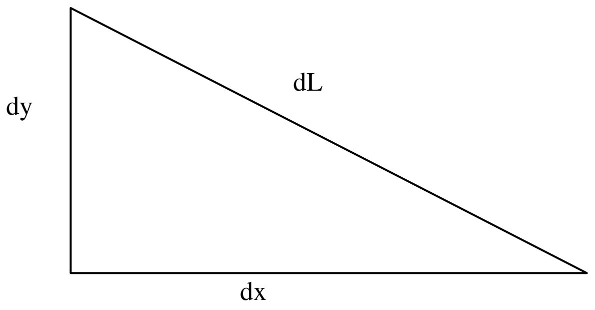


Figure 7. Convergence of Summed Segment Length Method

The summation methods presented in this section and the previous approach are clearly precursors to an integral method. To complete this line of thought, it makes sense to extend the method to a true integral. The length of an infinitesimal section of an arc is simply defined using the Pythagorean Theorem (Figure 8).



$$dL = \sqrt{dx^2 + dy^2}$$
$$= \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx$$

Figure 8. Length of an Infinitesimal Arc Segment

$$\frac{dy}{dx} = \frac{-x}{\sqrt{1-x^2}} \quad and \quad \left(\frac{dy}{dx}\right)^2 = \frac{x^2}{1-x^2}$$
$$so \quad \sqrt{1+\left(\frac{dy}{dx}\right)^2} = \sqrt{\frac{1}{1-x^2}} \qquad (8)$$

Since the circumference of the full circle is 2π, the arc length of the quarter circle is π/2 and

$$2\int_0^1 \sqrt{\frac{1}{1-x^2}}\,dx = \pi \qquad (9)$$

The methods shown so far require an entirely new calculation for each increase in N. While this may seem like a trivial distinction, it is important when calculating a large number of significant figures. A more useful approach would be one in which increasing the number of terms in the estimate meant simply adding new terms to ones that had already been computed. This leads to infinite series approximations.

Series Expansion Approximations

The purpose of this exercise is to develop an expression that allows calculating approximations to π of arbitrary accuracy. A common method for doing this is a Taylor series expansion or its simpler variation, the Maclaurin series expansion [6]. Many efficient methods of calculating numerical approximations to π are based on these series.

Most beginning calculus students learn that a Taylor series can be used to approximate a continuous function as long as the function is sufficiently smooth. They may even know that scientific calculators use series approximations internally to evaluate familiar functions like sin(x) and cos (x). The general expression for the Taylor series is

$$f(x) = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \ldots \qquad (10)$$

where “a” is a constant (the number about which the series is expanded). If a = 0, the Taylor series becomes a Maclaurin series.

$$f(x) = f(0) + \frac{f'(0)}{1!}x + \frac{f''(0)}{2!}x^2 + \frac{f'''(0)}{3!}x^3 + \cdots \qquad (11)$$

Technology students tend to be more receptive to concepts that can be presented graphically. As an example, the Maclaurin series expansion for tan(x) is

$$\tan(x) \approx x + \frac{1}{3}x^3 + \frac{2}{15}x^5 + \frac{17}{315}x^7 + \cdots \qquad (12)$$

Figure 9 shows tan(x) in the range 0.5 ≤ x ≤ 1.5 along with increasingly accurate series approximations. It is clear that increasing the number of terms in the approximation produces approximating functions increasingly close to tan (x).

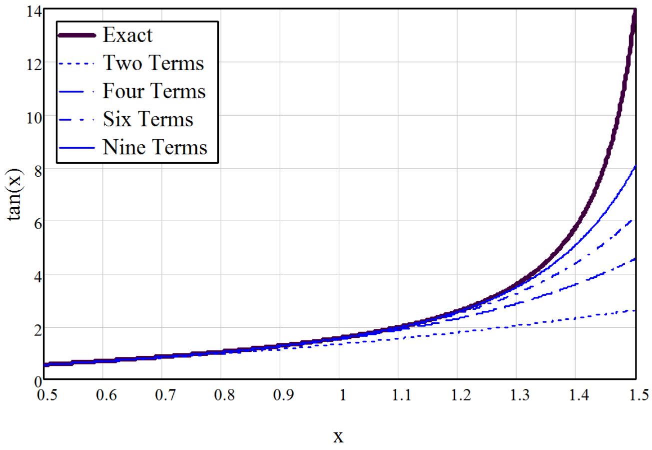


Figure 9. Series Approximations to tan(x)

Being able to approximate a range of expressions with an infinite series opens a new class of functions to be used for approximating π. Since tan(45°) = tan(π/4) = 1, one of the first, and perhaps the most obvious, of these was $\tan^{-1}(1)$ = π/4. Written as a Taylor series, $\tan^{-1}(x)$ is

$$\tan^{-1}(x) = \tan^{-1}(a) + \frac{1}{1+a^2}(x-a) + \frac{-a}{\left(1+a^2\right)^2}(x-a)^2 + \left[\frac{8a^2}{\left(1+a^2\right)^3} - \frac{2}{\left(1+a^2\right)}\right]\frac{(x-a)^3}{3!} + \cdots \tag{13}$$

An approximate expression for π = 4tan^{-1}(1) is, thus,

$$\pi = 4\left[1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} + \cdots + \frac{-1^{N+1}}{2N-1}\right] \tag{14}$$

Figure 10 shows the convergence of this series. It is unique among the series discussed so far in that it alternately overestimates and underestimates the correct value. More important, though, is the fact that the series converges very slowly. This problem is well known and there are other series that converge more quickly.

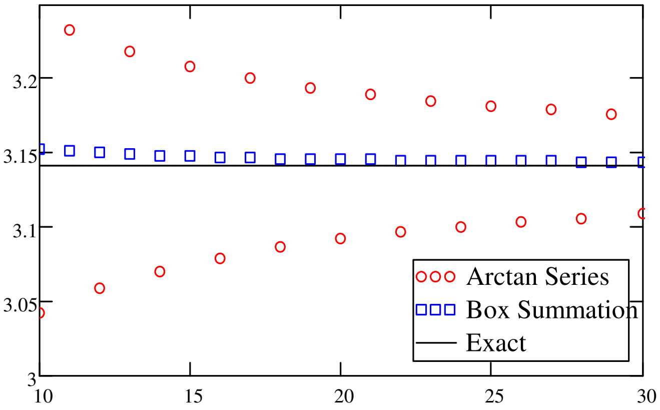


Figure 10. Convergence of Maclaurin Series for Arctan Approximation

Any change to the process that increases the rate at which successive terms decrease in magnitude should increase the rate of convergence. One possibility is to use an angle smaller than 1 radian so that the magnitude of the x^n terms in the Maclaurin series decreases much faster. This may require a change in the function being considered. Specifically, sin(π/6) = ½, so 6sin^{-1}(1/2) = π. The Maclaurin series expression is

$$\pi = 6\sin^{-1}\left(\frac{1}{2}\right) = 6\sum_{n=1}^{\infty}\frac{(2n)!}{4^n(n!)^2(2n+1)}\left(\frac{1}{2}\right)^{2n+1} = 6\left[\frac{1}{2} + \frac{1}{48} + \frac{3}{1280} + \frac{5}{14336} + \frac{35}{589824} + \cdots\right] \tag{15}$$

Note how quickly this series converges, as shown in Figure 11. A six-term series yields 3.1415767, about 99.9995% of the right answer. Since π is irrational, there is no exact numerical value and no way to precisely state the difference between the calculated number and the accepted value. For our purposes, the "exact" answer is assumed to be the value programmed into Mathcad, which is correct to seventeen decimal places.

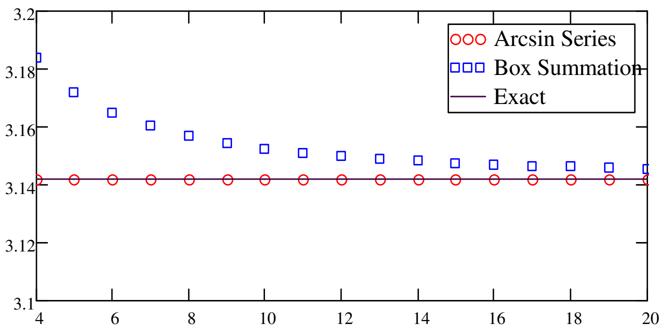


Figure 11. Convergence of Maclaurin Series Expression for 6sin^{-1}(1/2)

Finally, let's revisit the integral expression in Equation 9. The integrand can be expressed using a Maclaurin series approximation.

$$\sqrt{\frac{1}{1+x^2}} = 1 + \frac{x^2}{2!} + \frac{3^2x^4}{4!} + \frac{5^23^2x^6}{6!} + \frac{7^25^23^2x^8}{8!}\cdots \tag{16}$$

There are a number of different integration limits that could be used, but some converge faster than others. Equation 9 calculates the circumference of a quarter circle, so the range of integration is 0 to 1. Since the integral of Equation 16 is a summation of terms of the form cx^n, the upper integration boundary affects the rate of convergence. If the upper limit of integration is 1, then the each term reduces to c×1^n = c. However, if the upper limit is less than 1, then the magnitude decreases much more quickly as the value of the exponent, n, increases.

The constraint is that the upper limit must correspond to some rational, preferably integral, multiple of the circumference of a circle. Fortunately, an upper integration limit of ½ corresponds to an angle of 30° and the resulting arc length is 1/12 the length of the circumference. The resulting expression is

$$\pi = 6\int_0^1 1+\frac{x^2}{2}+\frac{3^2x^4}{4!}+\frac{5^23^2x^6}{6!}+\frac{7^25^23^2x^8}{8!}+\cdots$$

$$=6\left[\frac{1}{2}+\frac{1}{3!}\left(\frac{1}{2}\right)^3+\frac{3^2}{5!}\left(\frac{1}{2}\right)^5+\frac{5^23^2}{7!}\left(\frac{1}{2}\right)^7+\cdots\right] \qquad (17)$$

$$=6\sum_{n=0}^{N}\frac{\prod_{i=0}^{n}(2i-1)^2}{(2n+1)!}\left(\frac{1}{2}\right)^{2n+1}$$

While this may look like a new expression, a little algebra shows that it is identical to Equation 15. It is interesting that two completely separate arguments can yield the same series approximation, a fact that clearly suggests the two starting expressions are related.

More Advanced Methods

More curious students may want to know about the most advanced methods of calculating π. As this is written, it is now known to approximately 1.24 trillion digits. For such a huge calculation, efficiency is critical. There are a number of different expressions, but most involve series expansions of trigonometric expressions. A particularly efficient expression was proposed by Machin [3].

$$\pi = 16\tan^{-1}\left(\frac{1}{5}\right)-4\tan^{-1}\left(\frac{1}{239}\right) \qquad (18)$$

This is written as a series expression by substituting the MacLaurin series approximation for the arctan function.

$$\tan^{-1}x = x-\frac{x^3}{3}+\frac{x^5}{5}-\frac{x^7}{7}+\ldots \qquad (19)$$

A four-term series using this expression differs from the “exact” value by less than one part in 10^6.

A more recent expression was developed by Takano [7].

$$\pi = 48\tan^{-1}\left(\frac{1}{49}\right)+128\tan^{-1}\left(\frac{1}{57}\right)- 20\tan^{-1}\left(\frac{1}{239}\right)+48\tan^{-1}\left(\frac{1}{110443}\right) \qquad (20)$$

A four-term series using this expression differs from the “exact” value by less than one part in 10^{14}.

The origin of “Machin-like” formulae lies in complex numbers. This is a particularly useful feature, since complex numbers seem to be a source of continual confusion among engineering technology students. Students were shown how to derive one of these formulae by starting with the simple expression, (2+i)(3+i) = 5+5i. It is a simple task to present this expression graphically in the real-imaginary plane. Presented graphically in polar form, the two numbers are represented in Figure 12 below.

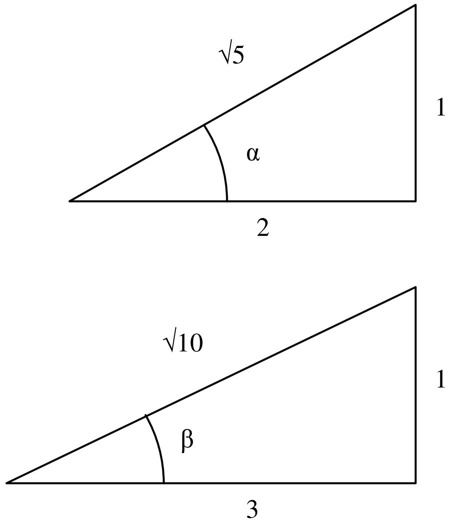


Figure 12. Polar Representation of Complex Numbers

In polar notation, the complex multiplication is

$$\sqrt{5}\angle\alpha\times\sqrt{10}\angle\beta=\sqrt{50}\angle\alpha+\beta \qquad (21)$$

5+5i = √50 Ðπ/4, so α+β = π/4 and

$$\pi = 4\left[\tan^{-1}\left(\frac{1}{2}\right)+\tan^{-1}\left(\frac{1}{3}\right)\right] \qquad (22)$$

This expression is slightly less efficient than the one in Equation 15. However, it leads directly to the other, more efficient expressions such as Equation 18. Figure 13 shows a comparison of convergence between the arcsin expression from Equation 15, Machin’s expression from Equations 18 and 22. The vertical axis shows the magnitude of the difference between the N-term series approximation and the value of π programmed into Mathcad.

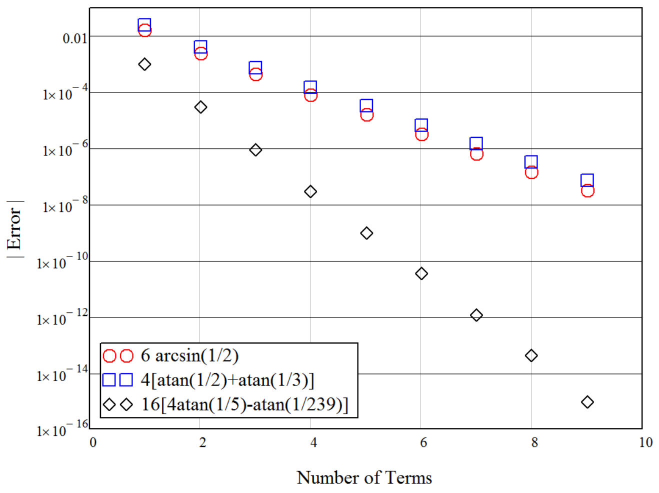


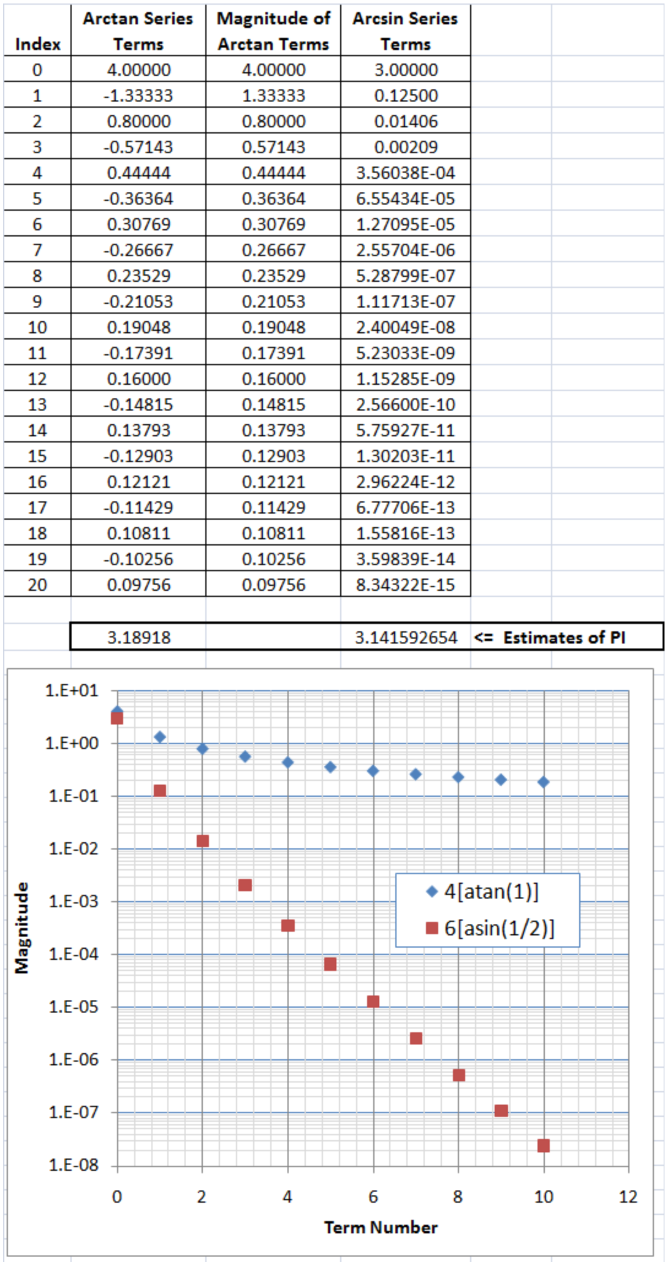
Figure 13. Comparison of Convergence for Inverse Trigonometric Expressions

Calculation Using Familiar Mathematical Tools

In order for the idea of calculating π to be made real to engineering technology students, the students need to do the calculations themselves and see how the individual steps work. While any of the methods presented here could be implemented on a scientific calculator, this is a chance to use software tools. The examples presented here will use Equations 4 and 15.

While not ideally suited to technical calculations, spreadsheet programs such as Excel can be useful, particularly when simple plots are needed. Figure 14 shows a sample calculation using the arctan and arcsin series methods. Because of the great differences in the rates of convergence, it makes sense to plot the magnitude of the individual terms in each series. The terms of the arcsin series decrease much more rapidly than the arctan series. By the 10th term, they are about seven orders of magnitude apart. This is a very compelling way of showing students graphically how differences in the formulation of the problem affect how much effort it takes to calculate a precise result.

Figure 15 shows a typical calculation using Mathcad. The nature of the program allows students to write out the series expressions in a clear format. It is easy to plot the convergence of the box summation method directly since the number of boxes can be specified as a parameter of the function being plotted. Additionally, Mathcad includes symbolic manipulation tools so that students can develop series expressions symbolically if they wish.

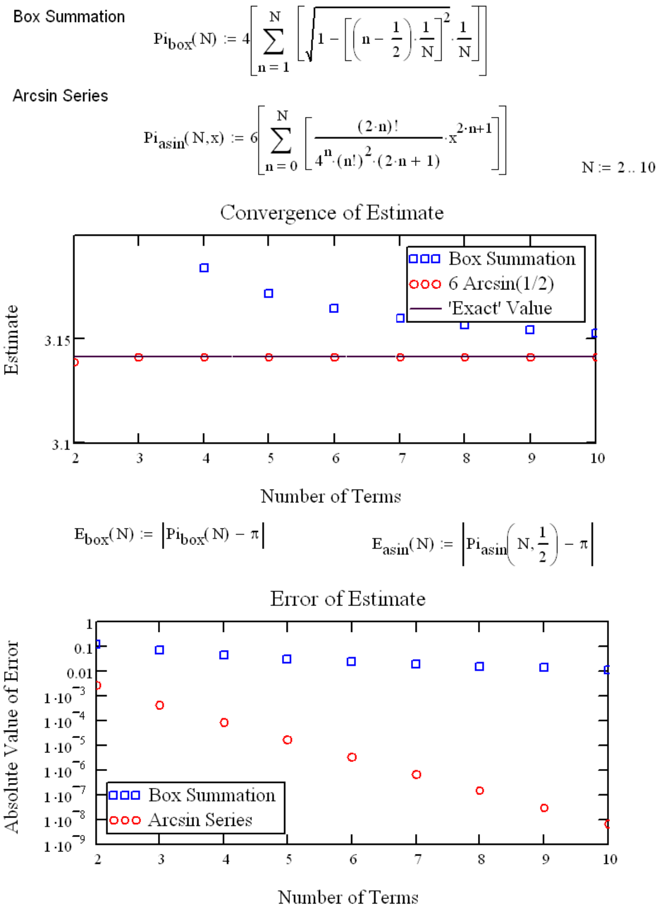


Index	Arctan Series Terms	Magnitude of Arctan Terms	Arcsin Series Terms	
0	4.00000	4.00000	3.00000	
1	-1.33333	1.33333	0.12500	
2	0.80000	0.80000	0.01406	
3	-0.57143	0.57143	0.00209	
4	0.44444	0.44444	3.56038E-04	
5	-0.36364	0.36364	6.55434E-05	
6	0.30769	0.30769	1.27095E-05	
7	-0.26667	0.26667	2.55704E-06	
8	0.23529	0.23529	5.28799E-07	
9	-0.21053	0.21053	1.11713E-07	
10	0.19048	0.19048	2.40049E-08	
11	-0.17391	0.17391	5.23033E-09	
12	0.16000	0.16000	1.15285E-09	
13	-0.14815	0.14815	2.56600E-10	
14	0.13793	0.13793	5.75927E-11	
15	-0.12903	0.12903	1.30203E-11	
16	0.12121	0.12121	2.96224E-12	
17	-0.11429	0.11429	6.77706E-13	
18	0.10811	0.10811	1.55816E-13	
19	-0.10256	0.10256	3.59839E-14	
20	0.09756	0.09756	8.34322E-15	
	3.18918		3.141592654	<= Estimates of PI

Figure 14. Example Calculation using Excel

Student Response

The calculations presented here were used in a mathematics review class as a learning module. An informal survey of students after the end of the class showed several themes in the students' perception of this exercise. The overall response from the students was positive and they clearly wanted to see this module remain in the syllabus. The first theme in the student responses was the clear utility of the result. While the mathematical concepts underlying the various calculation methods presented here could be easily presented in the context of a made-up problem, the central role of π in technical calculations clearly created interest among the students.



Box Summation

$$Pi_{box}(N) := 4\left[\sum_{n=1}^{N}\left[\sqrt{1-\left[\left(n-\frac{1}{2}\right)\cdot\frac{1}{N}\right]^{2}}\cdot\frac{1}{N}\right]\right]$$

Arcsin Series

$$Pi_{asin}(N,x) := 6\left[\sum_{n=0}^{N}\left[\frac{(2\cdot n)!}{4^{n}\cdot(n!)^{2}\cdot(2\cdot n+1)}\cdot x^{2\cdot n+1}\right]\right]$$

$N := 2 .. 10$

$$E_{box}(N) := \left|Pi_{box}(N) - \pi\right| \qquad E_{asin}(N) := \left|Pi_{asin}\left(N,\frac{1}{2}\right) - \pi\right|$$

Figure 15. Example Calculation Using Mathcad

A closely related theme in the comments was that students liked knowing what the answer should be when they started making their own calculations. In response, I pointed out that I could have given them the answer beforehand for any problem I had assigned. However, this wasn't enough for them. Their familiarity with the number π appears to be important. They all clearly knew what π was and many had memorized its value to more decimal places than they would ever need, but none of them knew where the numerical value had come from. Being able to solve this little mystery clearly motivated some of the students.

There were two other comments worth mentioning. One was that calculating π presented a clear example in which complex numbers were useful and necessary. The other was that the idea of accelerating convergence was an example of optimization and increasing the efficiency of a process.

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Biography

MARK FRENCH received a B.S. in Aerospace and Ocean Engineering from Virginia Tech, Blacksburg, VA, in 1985; an M.S. in Aerospace Engineering from the University of Dayton, Dayton, OH, in 1988; and a Ph.D. in Aerospace Engineering from the University of Dayton, Dayton, OH in 1993. Currently, he is an associate professor of Mechanical Engineering Technology at Purdue University. His areas of research include experimental mechanics and musical acoustics. He has authored a textbook: *Engineering the Guitar*, Springer, 2008. Dr. French may be reached at rmfrench@purdue.edu.

VIRTUAL PROTOTYPING AND MECHATRONICS FOR 21ST CENTURY ENGINEERING

Ryne McHugh, Purdue University; H. Henry Zhang, Purdue University

Abstract

The modern era of machine design has put new pressures on designers. The requirement to design devices with more functionality has driven engineers to combine multiple disciplines to create smarter electromechanical machines. This has become known as mechatronics. Another requirement is to get designs to market in a considerably shorter time. Virtual Prototyping, through the combination of SolidWorks and LabVIEW, will enable engineers to meet these requirements and maintain a profitable business.

Introduction

The 21st century has ushered in a new era of machines and methods for design. The demand for more cost-effective, better, and more functional machines, coupled with an unstable economy and intense global competition, has put considerable pressure on engineers. They are expected to produce more complex systems at a better product value, lower cost and faster rate. This necessitates an entirely new paradigm for design.

Mechatronics is defined as the synergy of mechanical systems featured with its precision in electronic control and intelligence in the design of products and manufacturing processes [1-6]. Further, these disciplines can be rendered down to the functional structure of Mechatronics, reflecting the product's six aspects: microcontroller, power supply, mechanical body, sensing apparatus, precision mechanical actuators and communication systems. These methods contrast the old paradigm of electromechanical design.

In traditional designs, designers of electromechanical systems would use a sequential method. That is, the mechanical engineers would first establish the basic design. It would then be passed on to the electrical engineers, and finally to the control and software engineers. Figure 1 below illustrates this point. In modern designs, the traditional approach promotes neither communication nor synergy, while mechatronics design methodologies and systems do promote these values. Concurrent engineering in mechatronic design is the new paradigm. Mechanical, electrical, control and software engineers participate in a given design simultaneously. This is illustrated in Figure 2, which shows the design engineering departments in parallel [7].

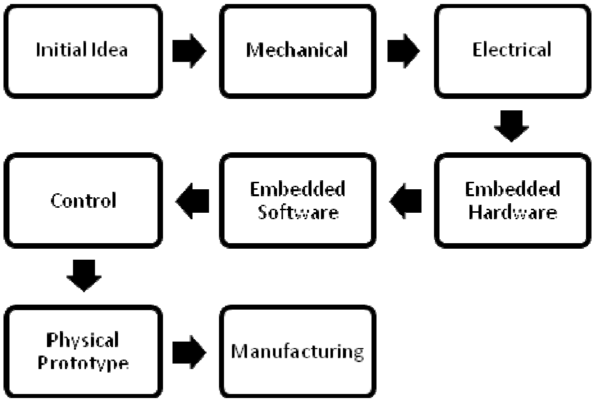

Figure 1. Traditional Design Method

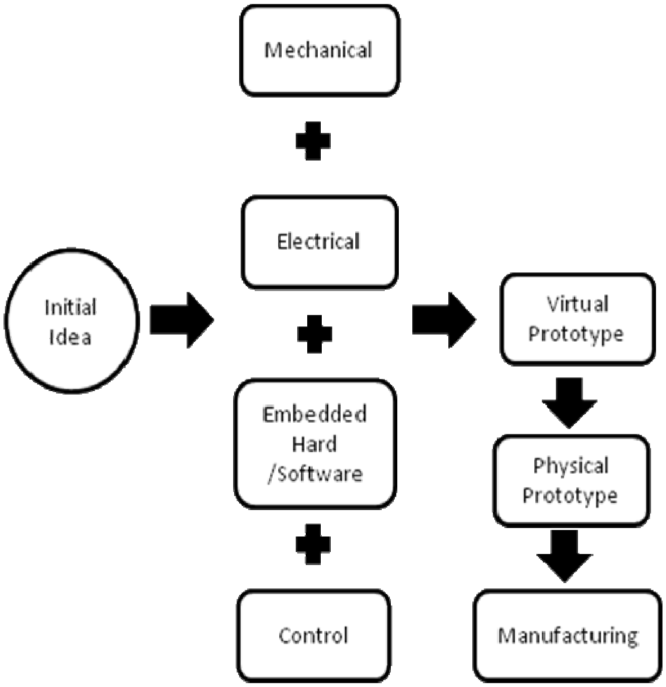

Figure 2. Modern Design Approach with Parallel Engineering Teams

For virtual prototyping (VP), concurrent engineering and successful synergy was difficult when the means to effectively communicate technical data and information was underdeveloped.[8-10]. This is a thing of the past because virtual prototyping and the associated software can facilitate these needs. Design engineering is on the cusp of change; mechatronics and virtual prototyping are positioned to enable that change. Prototypes are early models of equipment developed at full scale to be used for evaluating performance. Traditionally, these are physical prototypes built to identify problems in the initial design. They often lead to design changes and multiple iterations of the prototype as a means of optimizing the design. Creating multiple physical prototypes is extremely costly. Each new design demands more time, money and materials to realize the next iteration.

A virtual prototype is meant to serve the same function without the need for a physical model, thus reducing cost. When engineers discover the need for a change, and ways to optimize their design, they can simply alter the virtual prototype itself. This eliminates time- and money-consuming physical prototypes. Additionally, and perhaps more importantly, the initial design and virtual prototype can be created with simultaneous input from every engineer involved in the project. New software developments are enabling engineers to achieve optimized designs with fewer physical prototypes.

The essential techniques of virtual prototyping are reflected in the union of LabVIEW and SolidWorks [10-18]. National Instruments (NI), in combination with Dassault Systems, has developed a module that allows for a seamless union between NI's LabVIEW and Dassault's SolidWorks, known as the SoftMotion Module. This software allows the different design engineers to work simultaneously with CAD models, embedded software and control logic to simulate and analyze the dynamic behavior of a system.

Virtual prototyping with SolidWorks, LabVIEW and SoftMotion gives the mechanical and control engineering team a way to assess the function of the virtual mechatronic system in which the realistic machine operations are visualized, the cycle time throughput is simulated, and the product's performance and important information about the dynamic behavior of the design are demonstrated. In the past, these properties were explored mainly through the creation and testing of a physical prototype.

This study focused on virtual prototyping via 3D modeling and graphical programming, which is the trend in intelligent product design, and which is more intuitive for students not majoring in computer engineering and technology.

The 21st-Century Engineering

Industrial products in the 21st century will be mechatronic products, or smart machines. As stated before, mechatronics is meant to be a synergistic combination of multiple engineering disciplines. Mechatronic devices make use of microprocessors, data acquisition sensors and actuators, all within a mechanical body. What separates mechatronics from traditional electromechanical systems is the system's intelligence, logic and internal communication. Figure 3 illustrates this point.

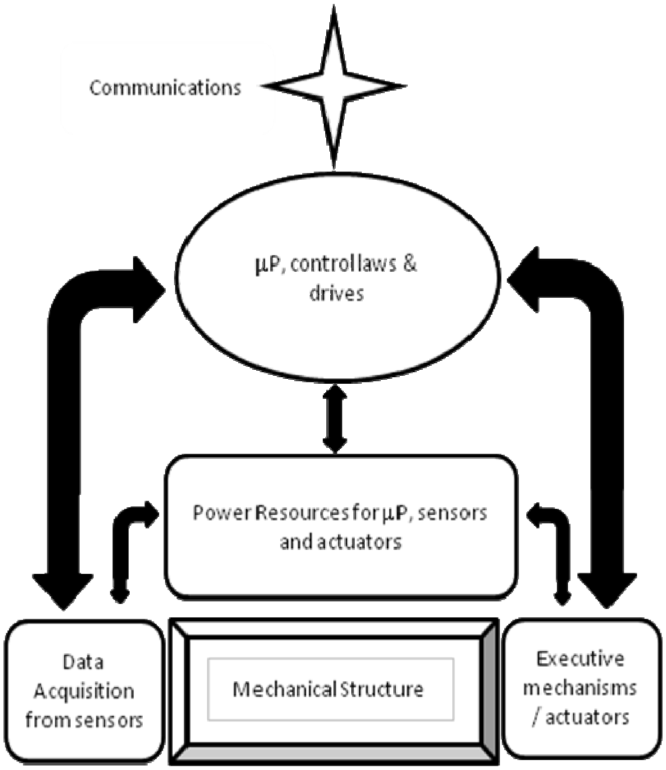

Figure 3. Synergy and Communication in Mechatronics

This is a very powerful combination of tools. If these systems are combined properly, the result is a machine that can be set to complete a task with minimal input from the user. The microprocessors and control logic allow mechatronic devices to react to inputs and make decisions based on these inputs. Therefore, nearly any process that requires mechanical actuation can be automated through the use of a synergistic mechatronics design. However, for engineers to successfully create a synergistic system, they need to work in a synergistic manner themselves. The traditional, "over the wall" technique does not allow them to do so. Virtual prototyping of mechatronics does.

Virtual prototyping is the integration of computer-aided design, embedded software programming and simulation software to visualize an intelligent mechatronics device in a computer environment. This environment allows design engineers to manipulate their models without the need for building a physical version. It has been commonplace in industry for decades to use CAD packages to develop solid models of mechanical designs. Programming and embedded logic have been widely used as well. The fact that these parts of the design were never developed in unison is what created a disconnect, especially in mechatronics design. Virtual prototyping with NI and Dassault software has changed that forever by bridging the gap.

National Instruments has developed an extremely useful tool known as the NI SoftMotion Module. This tool enables the combination of a SolidWorks 3D CAD model with a LabVIEW project tree. By doing so, all motors, sensors, gear trains, etc., defined within the CAD model can be connected with the LabVIEW algorithms developed to govern the model. The actuators are connected using the SoftMotion Axis tool. If using multiple axes together, the designer can create a coordinate space in which the axes will operate simultaneously. A model of the SoftMotion Module is demonstrated in Figure 4, which presents this process in a very easy-to-understand, graphical way.

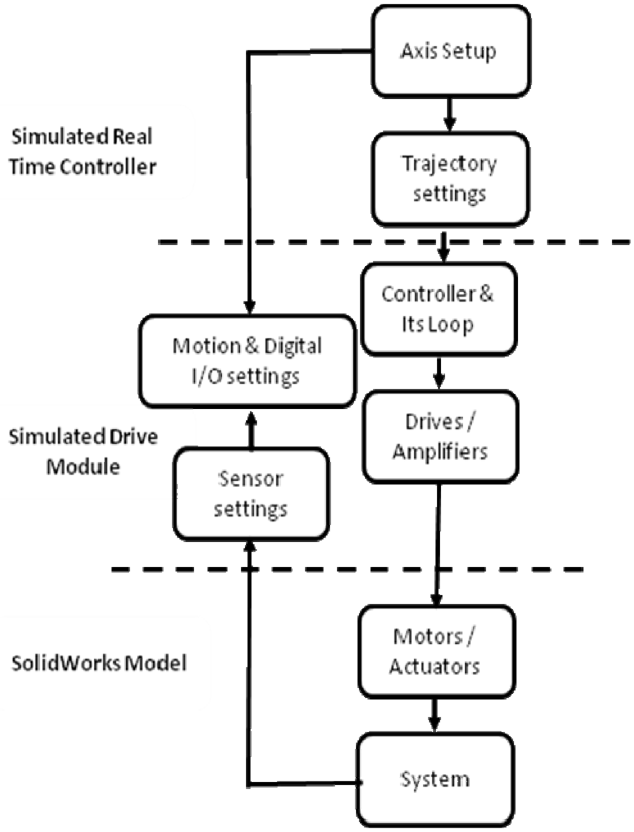

Figure 4. Motion Control System with SolidWorks

Once these steps have been completed, motion profiles can be created. The functions within the NI SoftMotion Module are used to move the profiles in a variety of ways. The movements can be as simple as a single-axis, straight-line movement or a complex, contoured motion. If properly programmed, complex, coordinated motion can be achieved. These tools allow the designer to manipulate the profiles as a means of optimizing the design. Figure 5 demonstrates a motion study of the enabled motors and their analysis using the SoftMotion Module.

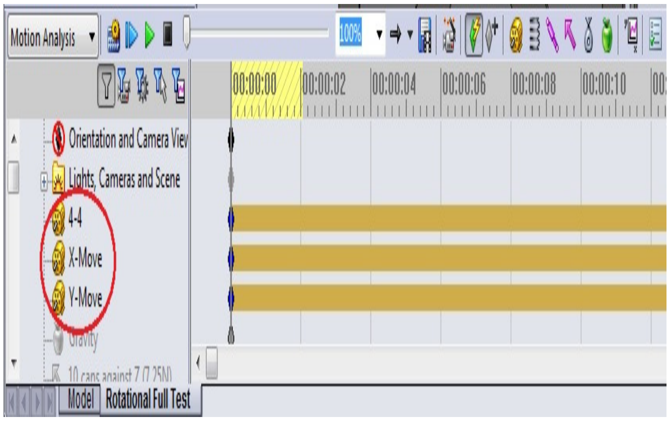

Figure 5. Motion Analysis and Motors Enabled

If the models are properly programmed and the appropriate connections are made in the software, a 3D CAD model in SolidWorks can now be brought to life for simulation and analysis. One of the few drawbacks for this method is the inability to perform real-time visualization. SolidWorks performs intense calculations to create the simulation, thus moving at a pace slower than real-time. The time, however, is accurate relative to the programmed timing. The results of a simulation can serve the purpose of visualizing machine operation, cycle-time estimation, accurate force and torque requirements, collision detection, validation of motion control programming, design optimization and identification of issues on the mechanical/electrical boundary. By means of collaboration between SolidWorks and LabVIEW, the mechanical dynamics, including mass and friction effects, cycle times and individual component performance, can be simulated without any physical parts. These dynamic effects will be especially precise when material mass properties are accurately programmed into the SolidWorks model. Making use of these analysis results is a very powerful way of optimizing a design and far less costly than doing so with a physical prototype. The benefits of virtual prototyping are numerous.

The purpose of every business is to generate profit. Engineering firms generate profit by producing products at a cost lower than what they are able to sell them for. Therefore, if virtual prototyping can reduce production costs, these firms can increase their profit margins. In addition, they will produce better and more efficient products that will increase sales and revenue. How do virtual prototypes reduce production costs? The most observable way is through the reduction of iterations of a physical prototype.

Physical prototypes are extremely costly. They require a large amount of input from the engineers as well as materials used to actually build it. Developing a prototype in a virtual environment will save huge amounts of money by reducing not only the input time required of the engineers, but also the materials used to bring it to life. Additionally, when a physical prototype must be redesigned, much of the material used to create it will go to waste. Virtual prototyping will reduce this waste as well. Risk is also reduced through the use of virtual prototyping. Every decision a business makes runs the risk of inducing an undesired outcome. VP can make engineers more confident in their designs, thus reducing the potential for undesired outcomes. Profits are increased by more than just the reduction of cost. Can virtual prototyping increase profits in other ways? The answer is yes.

Throughput is a somewhat elusive term used by businesses. With respect to design engineering, it can be thought of as the amount of information successfully transmitted from one place to another. By increasing the amount of throughput via virtual prototyping, firms can achieve more. The growing complexity of 21st-century mechatronics devices demands that engineers increase their throughput. Virtual prototyping does this by allowing the various engineering departments to communicate far more efficiently and work in parallel. Their ability to achieve more throughput has a threefold effect: increased functionality, optimization/customization opportunity, and marketplace dexterity.

It has been previously stated that functionality is the backbone of a 21st-century mechatronics design. This means that the machines themselves must be more functional. It also means that the models must be the same. When making a bid for a contract, who is more likely to win it? The company with basic CAD designs and a text-based description, or the company with a fully animated, dynamic, ready-to-optimize-and-customize, virtual simulation? The choice is clear.

Being able to stay flexible and react to a changing market is also very important. Customer needs change and businesses must be able to meet those changing needs if they intend to keep their clients. The use of VP allows firms to make changes and reach final designs more quickly. This enables them to meet customer needs faster. Furthermore, given the appropriate situation, customers and suppliers could work side by side (much like the aforementioned parallel engineering concept) to achieve a mutually beneficial design concept. Considering the current state of the economy, these are all extremely useful benefits of using virtual prototyping.

Examples and Applications

There are many mechatronic systems in use today. Hybrid gas-electric vehicles and wind turbines, for example, are some of the most complex mechatronic devices and they are becoming more and more prevalent. Purdue's Mechanical Engineering Technology Department has built a physical prototype a mechatronic device: a two-wheeled, self-balancing scooter, as shown in Figure 6. This physical prototype was developed without the use of a virtual counterpart. The final cost was greater than $5,000. This could have been significantly reduced if certain design considerations could have been made prior to the physical prototype being built. The methodology for doing so is quite simple.

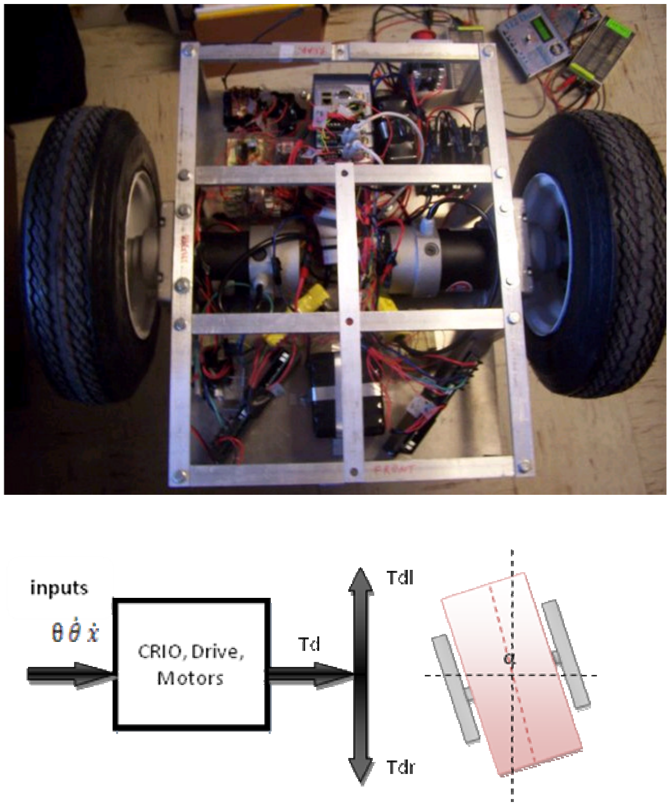

Figure 6. MET Two-wheeled, Self-Balancing Scooter

Virtual prototyping has been clearly defined, the software needed, identified and its benefits outlined. But what steps should be taken within each software package in order to reach the optimal design? The flowchart shown in Figure 7 illustrates a simple algorithm for use as a guide in the creation of a virtual prototype. The numbers shown in rectangles are reference points for the solutions of Table 1, and which are used for the Analyze section of the algorithm.

Table 1 is meant for use with Figure 7 in the following way. The designer follows Figure 7 to produce the VP. When analyzing the VP, the questions under "Analysis" in Table 1 should be asked. If the answer to the question is no, the designer should refer back to Figure 7 and the step that is associated with the number in the "Solutions" column. However, if Table 1 refers you back to solution number 2 or 3, the following section details further the appropriate steps to correct the analysis problem. Certainly there are more questions that could be asked and further analysis that could be done, but the scope of this study did not allow for everyone to be detailed.

The analysis solution number 2 suggests returning to the "create motion profile" phase within LabVIEW. By doing so, one can change the path of motion to avoid collisions or optimize the cycle time. Figure 8, Adjusting Motion Profile with LabVIEW, details the steps to accomplishing this task. Solution number 3 sends the user back to SolidWorks to adjust the details of the material. This step can solve problems related to strength, friction, weight, etc. The flowchart of Figure 9 details specifically what must be done in order to make changes to the material properties of the solid model.

Table 1. Analysis Table for Optimization of VP in Figure 7

Analysis	Solutions
Were there any collisions?	1 2
Is there a better material option?	3
Is there excessive friction?	1 3
Is there excessive torsional load?	1 3
Are limit switches appropriately placed?	1
Was the cycle time optimal?	1 2 4
Is the mechanical device strong enough?	1 3
Did the machine accurately perform tasks?	4

Conclusions

Mechatronic devices will dominate the 21st century. The requirement that engineers continue to increase functionality will drive the industry and virtual prototyping will become an ever more valuable tool as a means to that end. Fortunately, National Instruments and Dassault Systems have joined forces to make virtual prototyping a reality. As companies are required to be more efficient, virtual prototyping will become more popular. The design process will never be the same, and it would appear that this process is moving in the right direction.

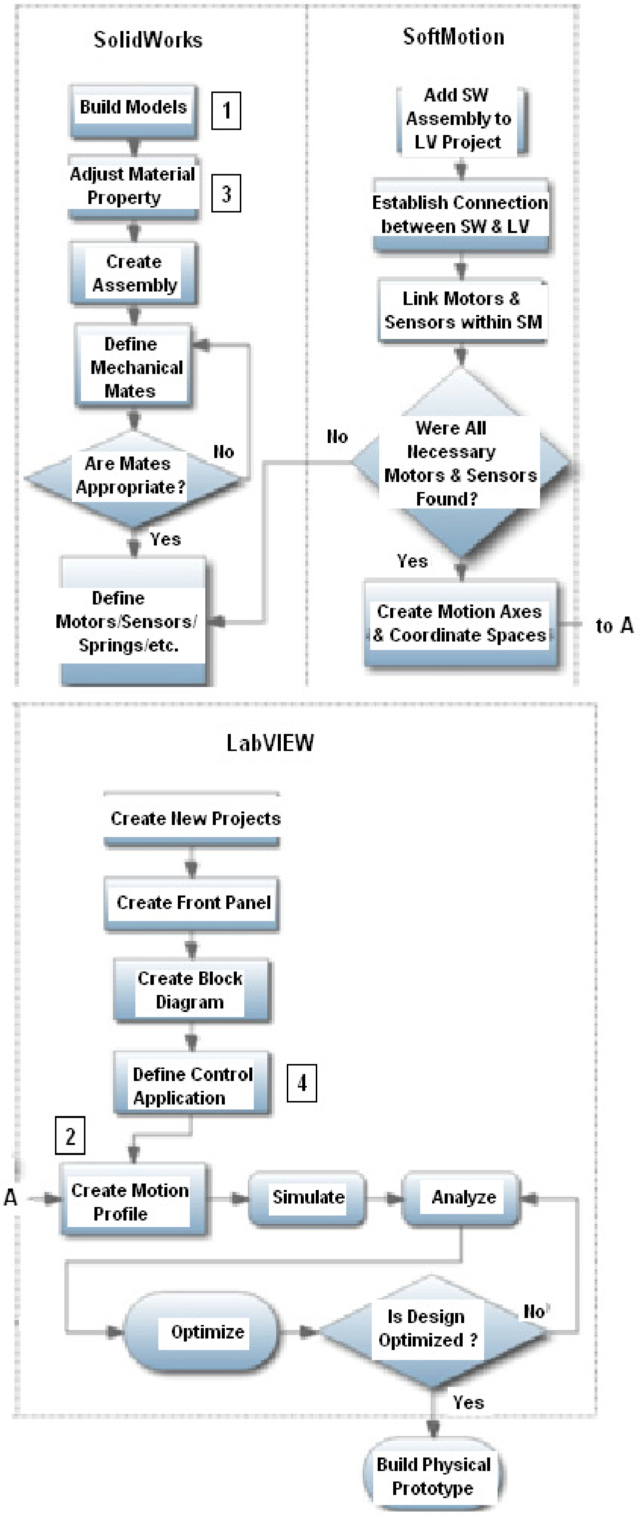

Figure 7. VP Flowchart with SW, LV and SoftMotion Module

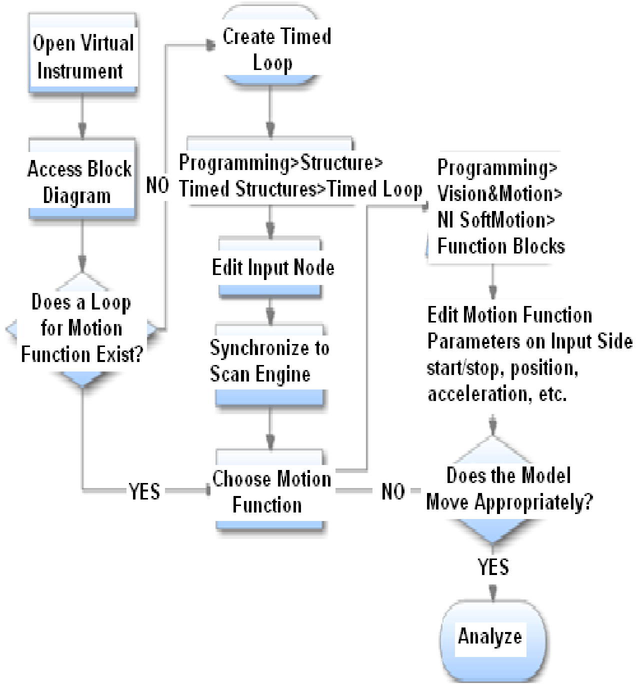

Figure 8. Adjusting Motion Profile with LabVIEW

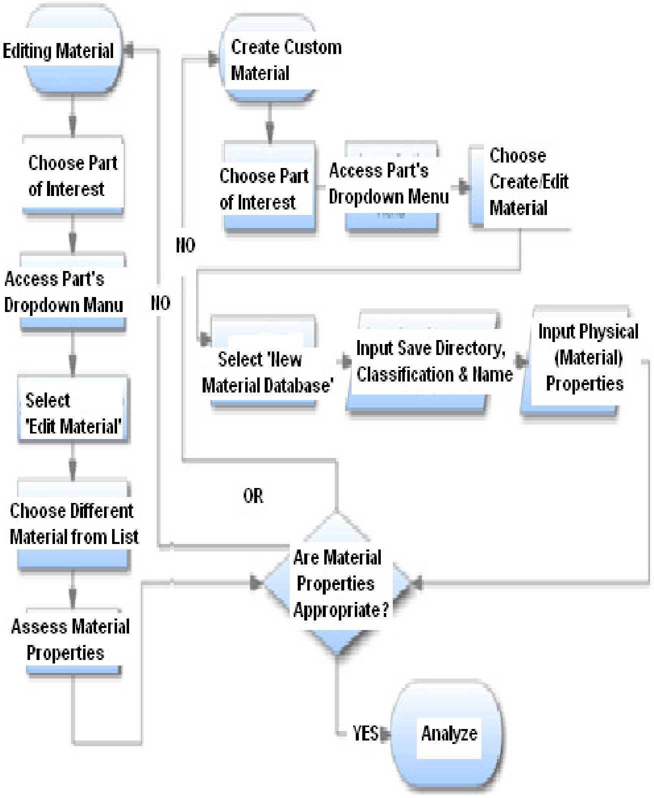

Figure 9. Adjusting Material Properties with SolidWorks

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DEVELOPMENT OF A BENCH-TYPE EXPERIMENT FOR AN ELECTRIC-DRIVE VEHICLE POWERTRAIN

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Abstract

The industry consensus is that vehicle electrification is the currently available technology for increasing propulsion system efficiency and decreasing pollutant emissions. However, the electric drivetrain operates much differently than conventional vehicle powertrains. There is a need for training automotive engineers and educating students in this new and emerging technology of electric drivetrains. In this study, an interactive, industrial-component-based bench unit was developed as an educational tool for two different configurations of electric drivetrains: battery-electric and series-hybrid electric. The unit is capable of demonstrating, illustrating and displaying multiple energy flows in the electric-drive vehicle, based on its configuration and driving conditions. The integrated unit serves as a hands-on-experience workstation for multidisciplinary students enrolled in the electric-drive-vehicle technology courses. The hands-on experience not only enhances their vehicle electrification training and education, but also sparks student interest in the green movement of transportation.

Introduction

The new Corporate Average Fuel Economy (CAFE) standards were passed to decrease our dependence on fossil fuels by increasing the standards on new vehicles to 35.5 miles per gallon (MPG) by model year 2016 [1-2]. One important method of actualizing this required efficiency is vehicle electrification. Vehicle electrification involves electric drivetrain and electrically powered automotive auxiliary subsystems that are at the heart of Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV). The electric drivetrain operates much differently than conventional vehicle powertrains. Therefore, existing development, design and maintenance techniques, and guidelines created for conventional powertrains, do not apply well to electric drivetrains. There is a need for training automotive engineers and educating engineering students in this new and emerging technology of electric drivetrains.

In response to the need of a trained and educated workforce in vehicle electrification, several universities and colleges have recently developed projects, courses and degree programs for training students, automotive engineers and technicians in electric-drive vehicle technology [3-8]. Developing new education and training for electric-drive vehicles requires careful planning of laboratory equipment and facilities. Existing courses in power electronics and electrical machines can be expanded and their laboratory resources leveraged with moderate cost. However, the costs will increase if the instruction includes hands-on experience with electric-drive propulsion components or dynamometer testing equipment. An overview course can be introduced with minimal laboratory impact, provided existing electric machinery equipment already exists. Laboratory instruction can include exercises on DC motors, AC induction or synchronous motors to build a solid foundation of the basic principles of electromechanical conversion such as torque, power and efficiency. Vehicle subsystem tests could involve a vehicle chassis dynamometer, an electric motor dynamometer, and electronic control-unit integration.

Although several curricula, short courses and training programs have been developed and delivered in the emerging technology of vehicle electrification, very few integrated electric-drive vehicle laboratories have been established for educational purposes. Several project-based laboratory activities on instrumentation for electric-drive components have been presented [8-10]. Software-based computer simulators such as LabVIEW for virtual hybrid electric vehicles have also been reported [11-12]. The tremendous capital investment and tedious and time-consuming tasks required to establish a fully functioning vehicle electrification laboratory is convincing evidence that colleges and universities are in need of a low-cost unit (less than U.S. $5,000) with industrial, electric-drivetrain functionality.

The motivation behind this project was to develop an interactive, industrial-component-based bench unit for two different configurations of electric drivetrains (battery-electric and series-hybrid). The unit is capable of demonstrating, illustrating and displaying (on the digital screens) the multiple energy flows in the electric-drive vehicle based on its configuration and operating conditions. The integrated unit serves as a hands-on-experience workstation for multidisciplinary students enrolled in the electric-drive-vehicle technology courses. The learning-by-doing experience not only enhances their vehicle electrification training and education, but also sparks their interest in the green movement of transportation.

Features of Electric-Drive Vehicles

The potential features of HEV include engine idle stop-start, engine-off driving (pure electric vehicle launch), power boost (maximum acceleration) and energy recuperation (regenerative braking). These typical HEV features during a simple driving cycle are illustrated in Figure 1 where the shaded areas represent the engagement of the electric system. As previously mentioned, electric drivetrains include propulsion systems of BEV, HEV and PHEV. In the BEV, the batteries must supply all of the energy needs. There is no onboard charging system except for regenerative braking. The batteries provide the power to propel the vehicle and to power all accessories such as air conditioning and power steering. The traction power of the BEV is provided by an electric motor using electrical energy stored in a battery rather than utilizing a heat engine. The range, or distance, that a vehicle can travel when operating exclusively on electrical power is called the All Electric Range (AER).

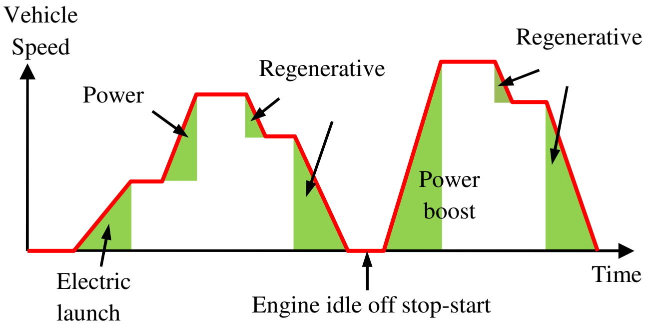
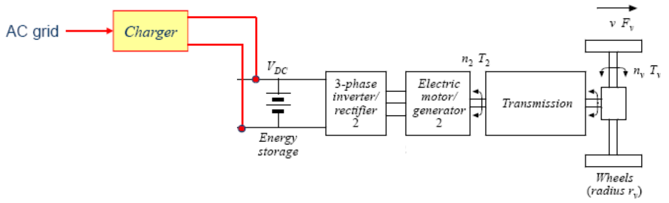
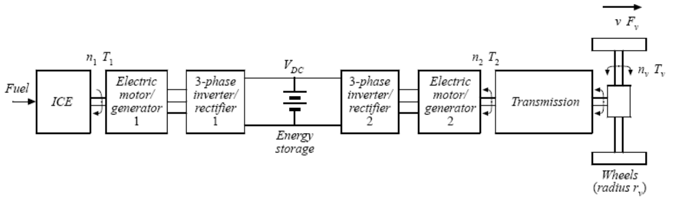


Figure 1. Energy Sources in a Typical HEV Subject to Driving Conditions

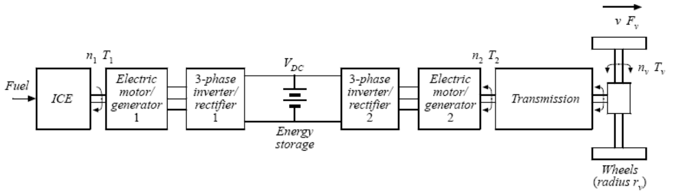
There are two basic HEV configurations, series and parallel. The main difference between them is how the propulsion power from the heat engine and electric machine are distributed. In a series HEV, a small heat engine directly drives a generator to generate electricity. The electricity is then distributed through the power bus, partially to drive the electric motor with the rest being stored in the battery pack. The engine turns on and begins to recharge the battery pack when it is drained to a certain level. The engine can be operated within a narrower and more efficient range of speeds because it is not directly connected to the drive wheels. However, the peak power required for acceleration and high -speed cruising is limited by the capability of the electric motor. A parallel HEV is configured with two power sources so that either the heat engine or the electric propulsion system, or both, can be used to produce the power to send to the drive wheels. Since the power from the heat engine and electric motor can simultaneously propel the vehicle, a higher peak power will be achieved compared with the series configuration. A mechanical coupler, such as a planetary gear set, for torque and speed summation is needed, which increases the complexity of packaging and control. Figure 2 show the typical layouts of a BEV, a series HEV and a parallel HEV [13].



(a) BEV



(b) Series HEV



(c) Parallel HEV

Figure 2. Typical Layouts of Electric-Drive Vehicles [13]

The bench unit developed in this study is capable of demonstrating the features of the BEV and series HEV electric propulsion systems. This includes the charge-depleting mode of the BEV during which the vehicle travels on electric power alone until its battery's State Of Charge (SOC) is depleted to a predetermined level. The charge-sustaining mode is also demonstrated in the bench unit for a series HEV. A series HEV combines the operation of the two energy sources in a manner such that the vehicle operates as efficiently as possible and keeps the battery SOC within a predetermined range.

Establishment of an Electric-Drivetrain Bench Unit

Figure 3 shows the block diagram of a teaching tool for the electric-drive powertrain bench unit. It is a state-of-theart combination of battery-electric and series-hybrid electric drive technologies. The major components include engine, alternator, system controller, battery, electric motor, voltmeter, current meter, switch, motor-speed controller and real vehicle accelerator pedal. A three-phase AC alternator is operated by an engine in the system. A battery controller (or a battery management system) is applied to manage the charging and discharging process of the battery pack. A DC motor controller drives the motor in order to achieve the desired torque-speed characteristic curve. The motor shaft connects to the tire via a rotating drum. The load applied to the tire from the drum simulates the road load. The system controller is a microprocessor-based system that is commonly taught and utilized in the engineering technology curricula and laboratory experiments [14-15].

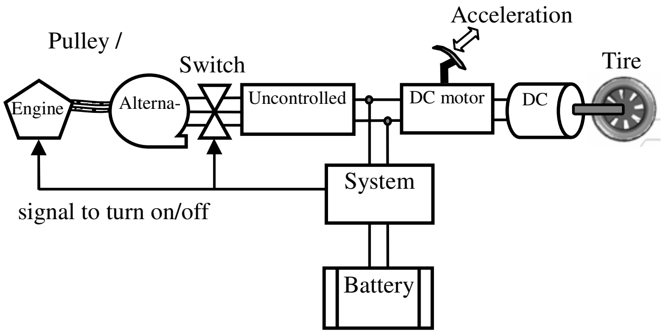


Figure 3. Schematic Diagram of the Electric-Drive Bench Unit

Hardware of the Bench Unit

The major components of the bench unit are listed in Table 1. Figure 4 illustrates the major components and their connections to the bench. There are four main functional blocks in the bench, as illustrated in Figure 4: battery and battery management, motor drive and brake system, internal combustion engine and alternator, and system controller.

- Battery and battery management
  By measuring the current flow and voltage at the battery terminal, the battery SOC meter will calculate and keep track of the remaining capacity of the energy in the battery. The output of the SOC meter is connected to the system controller to initiate the action of starting the engine and generating the charging current that will be sent to the battery.

- Motor drive and brake system
  The motor drive and brake system is designed to simulate the road load of the vehicle. Like normal vehicles, the accelerator pedal is used to command the speed controller to drive the motor. The brake system adds a load to the motor in order to consume the energy from the battery.

Table 1. Major Components of the Bench Unit

Engine	Generac, 250 c.c., 7.8 hp, OHV, electric and recoil start, horizontal
Alternator	Remy, automotive generator.
Battery	YTZ7S AGM maintenance free battery
Electric motor	Dayton, permanent magnet DC, 1 hp, 1800 rpm, armature 12 VDC.
Motor controller	Dart, 65E60-12, variable DC speed control, output voltage 12 VDC, power rating 1/8 – 1 hp, speed range 30:1, maximum current 60 amps.
Microprocessor	BasicATOM, Pro 28-M
Voltmeter	Blue Sea, 8028 DC analog micro voltmeter.
Battery SOC	Xantrex, LinkPro/LinkLite battery
Main switch	Motormite 85988, battery isolator
Fuse blocks	Littelfuse, MEGA, 298 series, 100A and 250A, 32V.

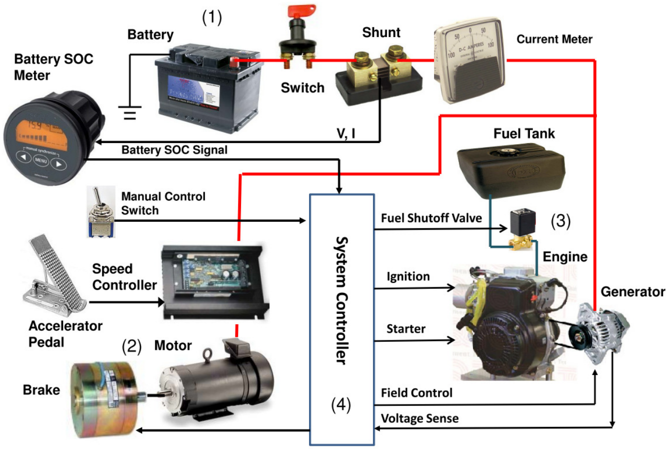


Figure 4. The Connections of the Hardware in the Bench Unit

- Internal combustion engine and alternator
  In the series HEV architecture, there is no mechanical connection from the internal combustion engine to the traction motor. The only device attached to the engine from the belt drive is the generator. For this demonstration bench, a vehicle alternator was coupled with the engine to generate electricity and charge the battery. The pulley ratios on both the engine and alternator shafts were carefully selected such that it would keep a minimum speed on the alternator to effectively generate power.

- System controller
  The system controller is the brain of the bench. It monitors the SOC of the battery from the Battery SOC meter and determines what, if any, action is needed by the engine and alternator. It will also control the current from the alternator and braking power of the brake.

Integration of the Bench Unit

The system controller, as shown in Figure 5, is a microprocessor-based device that includes five functions:

- The input filtering stage removes voltage spikes and noise in order to protect sensitive electronic components.
- The power supply will step-down the +12V from the battery to +5V for the microprocessor.
- The input-signal conditioning stage adjusts the input voltage level and filters noise from the wire harness.
- The microprocessor executes the software commends.
- The output driver stage will increase the current capability in order to drive external devices (solenoid).

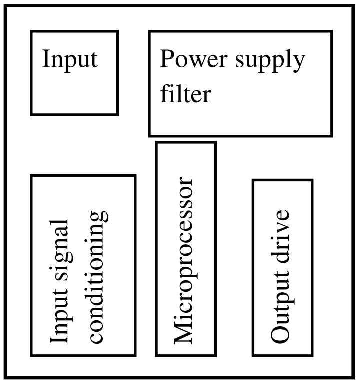


Figure 5. Microprocessor-Based System Controller

The detailed connection of the system controller is illustrated in Figure 6. The engine is connected directly to the alternator via a pulley and drive belt. The engine has an electric starter which is connected to the system controller via two connections:

1) The positive terminal of the starter is connected to the solenoid, which is connected to the starting relay in the system controller. The solenoid is also connected to the positive terminal of the battery. The negative terminal of the battery is directly connected to the negative terminal of the electric motor.

2) The wire coming out from the engine ignition coil to the manual ON/OFF switch is extended out and connected to the stopping relay in the system controller. The stopping relay replaces the original manual ON/OFF switch in the engine. The other end of the wire is connected to the spark plug. Thus, the stopping relay is the connection between the spark plug and the ignition coil and this connection is the secondary ignition circuit. The secondary ignition circuit always needs to be connected in order to avoid having the primary ignition circuit become activated. The secondary ignition circuit is active until it is connected and complete so that the primary circuit will not be activated. The reason to avoid the use of the primary circuit is that there is no control for stopping the engine, thus it will continue running until it runs out of fuel or is stopped by tempering the throttle and fuel ratio, which should only be done by a technically qualified person.

Four control signals are used to control the engine/alternator system. The fuel shutoff valve is the first signal that needs to be turned on before initiating the engine cranking sequence. Ignition and starter are two signals from the system controller to start the engine. Alternator field control is the signal to control the current output from the alternator. The engine cranking sequence will be automatically repeated in the event of an engine no-start that is detected by sensing the voltage produced from the alternator.

The alternator is connected to the battery and the system controller. The positive terminal of the alternator, denoted as BAT on the alternator, is connected with the positive terminal of the battery. The negative terminal of the alternator, denoted as GND on the alternator, is connected with the negative terminal of the battery. The direct connection between the alternator and the battery terminals is to ensure an active connection, even when the main switch is turned off. The purpose of making these direct connections is that in case the main switch is turned off all of a sudden, the alternator will still have a buffer (battery) connected to it to store the electric energy it generates. If a switch disconnects the battery from the alternator, the alternator will have no buffer to store the power it generates when the switch is turned off. When the sudden power generated by the alternator runs into the entire system, it will result in the burning of the microprocessor in the system controller and other electric devices in the system (voltmeter and current meter).

In the system controller, a 15Ω resistor is connected to the alternator field terminal, denoted as “F” on the alternator. The alternator selected for this bench unit was an automotive alternator which did not directly generate electricity during startup. The current passing through the 15Ω resistance to the field terminal on the alternator provides external energy to the field windings of the alternator. As the field windings get energized, the alternator produces the electric-

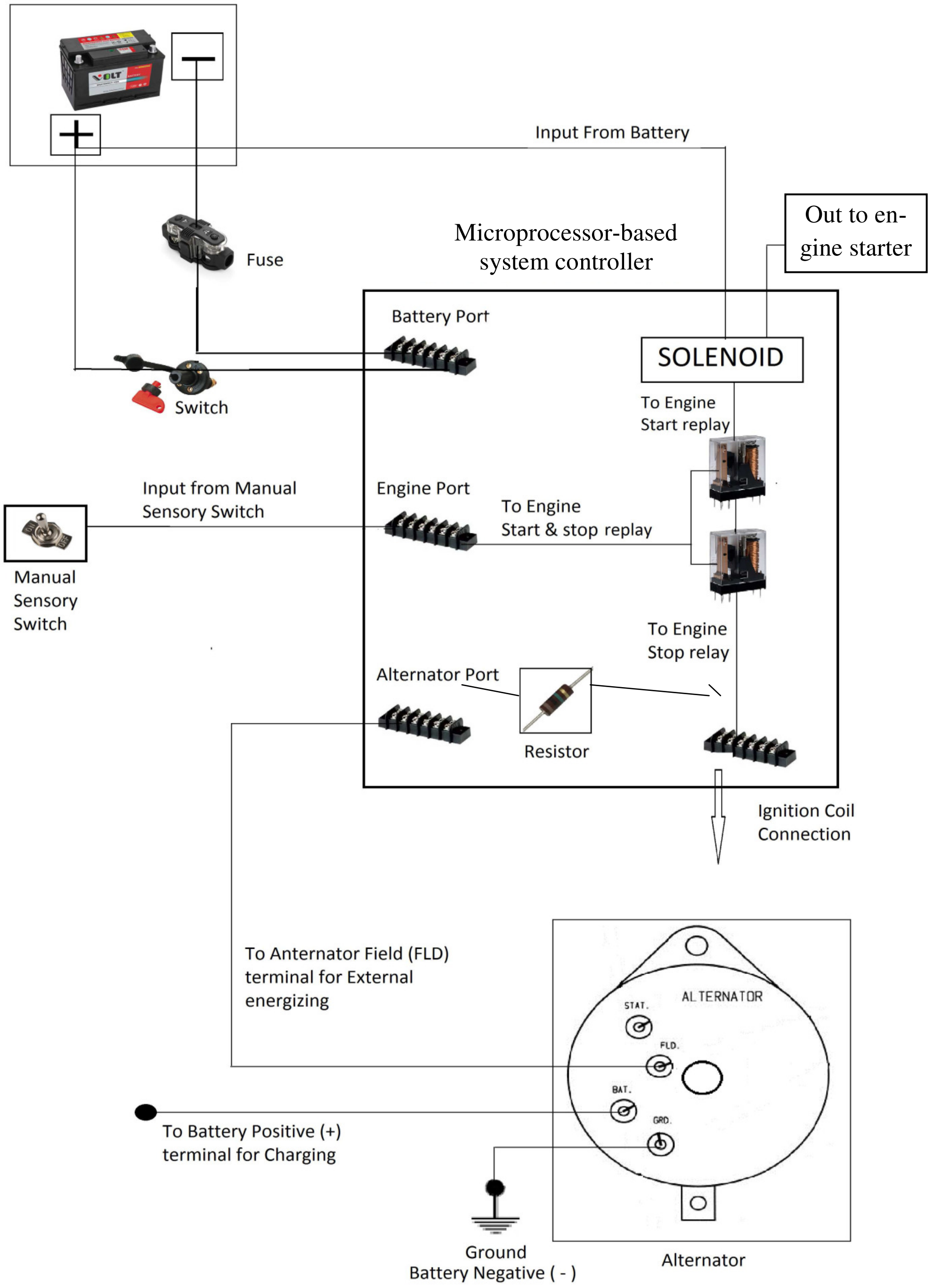


Figure 6. The Connections of System Controller

ity, which is then used to charge the battery. The resistance value is inversely proportional to the electrical output from the alternator. The value of the resistor was determined by several experiments. The 15Ω resistance was selected for generating the appropriate charging current to the battery in the system.

This controller is operated by a real vehicle accelerator pedal, or the throttle pedal. The accelerator pedal and motor controller were calibrated to provide a real feeling of driving. The motor stalls (no rotation speed) when the accelerator pedal is fully released. The motor speed is increased gradually according to how much and how fast the accelerator pedal is depressed.

The Bench Unit

The development of an electric-drive bench unit for use as a teaching tool was a team effort lead by a faculty member and group of undergraduate and graduate students, as shown in Figure 7. The team consisted of students with multidisciplinary backgrounds including mechanical engineering, electrical engineering and computer science. The task of development, design, layout, fabrication and assembly of the bench unit was done in the campus laboratory. The team also performed functional tests on the unit, modification of components, programming and system validation. The electric-drive bench unit is shown in Figure 8. The entire bench unit was installed on a movable cart. The cart can be moved to any classroom, laboratory, training room or demonstration and display area.

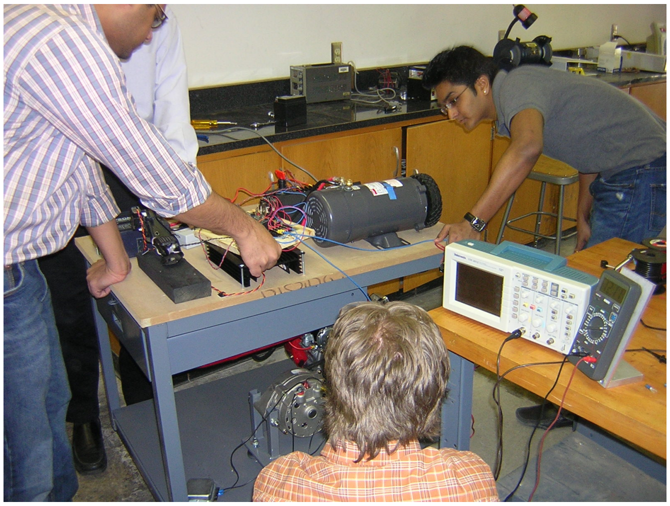


Figure 7. Students Working on the Unit

The battery and series-hybrid electric drivetrains were installed in the upper and lower portions of the cart, respectively. All of the battery electric-drive components–drive shaft, wheel, electric motor, motor controller, battery, system controller, and accelerator pedal–were installed on the top of the table. The engine, alternator and gasoline tank were mounted in the lower portion of the cart. The gasoline tank was installed in a specially designed drawer, which provides safety and convenience when filling the engine with gasoline.

The establishment of a functional electric-drive laboratory requires a tremendous investment of capital and time. One might think that the best option would be to purchase a production electric vehicle or hybrid electric vehicle for the laboratory. However, the manufacturer's warranty and safety will become issues when students tear down the vehicle and test the electric-drive components in the laboratory. Only a few commercial units for electric-drive training or education are available on the current market [16]. Some production-type electric powertrains can be modified for educational purposes; however, it is difficult to utilize all of the functions of the drivetrain in a laboratory environment.

Operations of the Electric-Drivetrain Bench Unit

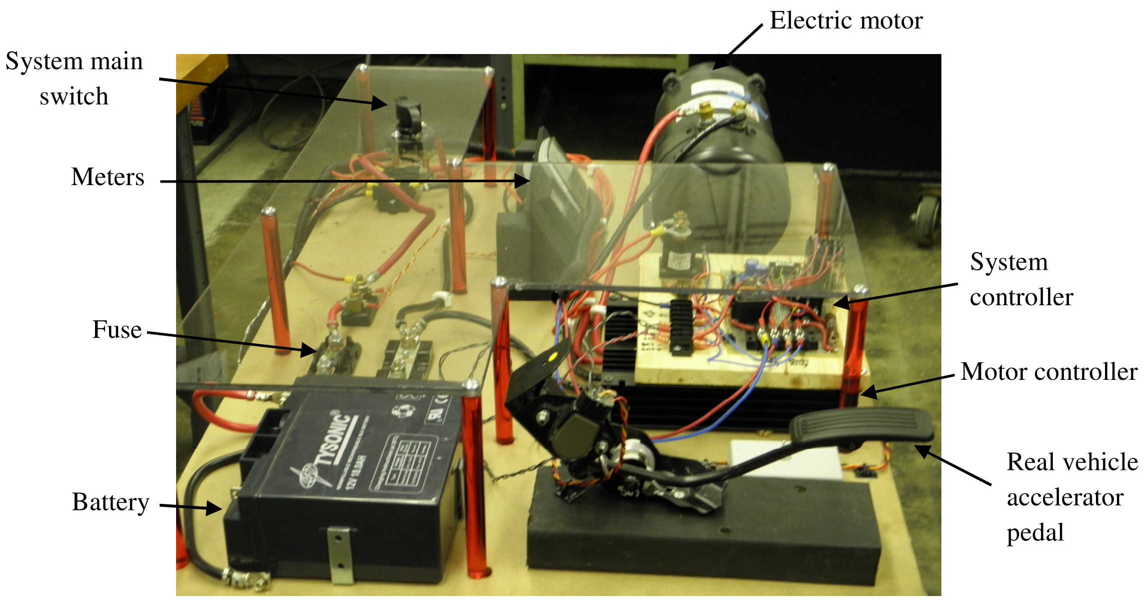
The electric motor draws energy from the battery and is the driving unit for the vehicle. The motor controller is used to control the speed of the motor and is operated by a real car accelerator pedal. The battery SOC or voltage can be checked by monitoring the voltmeter attached to the battery. Also, the operating status of the battery, charging or discharging, can be visualized by monitoring the current meter attached to the battery. Once the main switch of the system is turned on, the battery gets connected to the system controller and the power is delivered to the microprocessor. The operational stages are classified into BEV and series-HEV demonstrations:

BEV demonstration

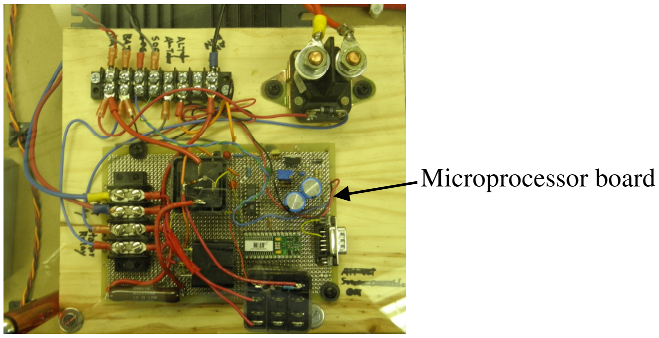
- The system is completely operational once the main switch of the system is turned on. The accelerator pedal can be depressed or released to any angles within the pedal's travel range. The position of the accelerator pedal determines the wheel speed.
- The engine and alternator are always off. The battery SOC/voltage is continuously depleted as long as the accelerator pedal is depressed.

Series-HEV demonstration

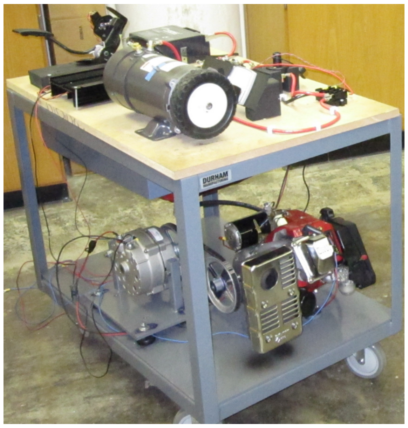
- The main switch of the system is turned on.
- As soon as the manual switch is triggered, it sends a signal to the system controller to trigger the solenoid switch through the starting relay.
- When the solenoid is triggered, the current is sent to the starting motor, which starts the engine.
- The starting motor gets current through the solenoid, which is triggered by the opening of the starting relay. This starting relay is programmed to stay open only for 5 seconds after it gets triggered. This means that the current supply to the starting motor stops after 5 seconds, which allows sufficient time to start the engine.
- The engine is connected to the alternator via a pulley and drive belt. Thus, the generator starts running along with the engine.
- The alternator is directly connected to the battery from its output so that the electricity generated by it can be directly stored in the battery.



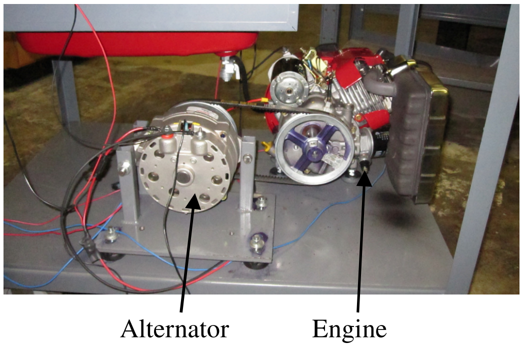
(a) Battery electric-drive portion on the top of cart



(b) Enlarged view of system controller



(c) Series electric-drive portion on the



(d) Belt connection between engine and alternator

(e) Metal screen covered rotational parts

Figure 8. A Developed Electric-Drive Bench Unit

- The entire circuit remains completed and active as long as the manual switch is depressed, and can remain so if needed. Once the switch is released, the trigger is off.
- The microprocessor is programmed in such a way as to control the engine's on and off conditions. As soon as the battery voltage/SOC reaches a pre-defined value, the stopping relay in the ignition is off and circuit opens. The open circuit breaks the supply of current to the spark plug, thus stopping the engine.
- The entire circuit stops once the engine stops, at which point the system operates in a BEV mode.
- The engine will be started again only when the battery voltage/SOC decreases below a pre-defined value.

Integration of the Electric-Drivetrain Bench with the Curriculum

The University has two degree programs and one graduate certificate program related to hybrid and electric vehicles: an M.S. degree program in Electric-Drive Vehicle Engineering (EVE), a B.S. degree program in Electric Transportation Technology (ETT), and a Graduate Certificate in EVE. Three courses have used this electric-drivetrain bench unit as part of the laboratory experiments for students. This bench unit provides students with practical, hands-on experiences that favor typical learning styles, encouraging students to learn by doing. The short description of each course is listed below.

EVE5110 *Fundamentals of Electric-drive Vehicle Engineering* (4 credit hours). This course provides an introduction to electric, hybrid and fuel-cell-hybrid vehicles explaining the advantages and disadvantages of electric-drive vehicles in comparison to conventional internal-combustion-engine vehicles. The fundamentals of electric machines, power electronics and energy storage devices for electric drives are provided and demonstrated in lab exercises. The application of electric drives in hybrid and electric vehicles utilizing a variety of powertrain architectures is presented. Elementary analyses of electric-drive vehicle performance and fuel economy are included.

EVE 5310 *Electric-drive Vehicle Modeling and Simulation* (4 credit hours). This course focuses on the overall energy conversion, storage, utilization and optimization of complete ground vehicle systems for conventional, hybrid and electric vehicles. A methodology for constructing general models of internal-combustion engines, electric machines, energy storage and power flow processes in hybrid and electric vehicles is developed and implemented using Matlab/Simulink, GT-Drive, or AVL/Cruise.

ETT4150 *Fundamentals of Hybrid and Electric Vehicles* (3 credit hours). General background of HEV-related technologies including technical concepts, design factors, energy analysis and unified modeling approaches is presented. Discussion of hybridization, hybrid powertrain architectures, internal-combustion engines for hybrid electric vehicles, associated types of transmissions used, PHEVs, fuel-cell vehicles and on-board energy storage is also presented.

The EVE5110 course was offered in the Fall 2010 term and had 21 students. The EVE5310 and ETT4150 were offered in the Winter 2011 term with 22 and 18 students enrolled, respectively. The students had several stand-alone laboratory experiments in each course, such as electric machines, power electronics, electric energy storage and control. Computer simulation software was also utilized in these courses for vehicle system and sub-systems modeling and simulation. The electric-drivetrain bench is an integrated unit consisting of all the major components in HEV/BEV and is capable of demonstrating, illustrating and displaying the multiple energy flows in the electric-drive vehicle based on its configuration and driving conditions. This integrated laboratory experiment provides students with the in-depth knowledge and hands-on experience of the interface and control of each component in each of the electric-drive propulsion systems.

Conclusion

An increasing quantity of production HEV/PHEV/BEV vehicles offers much promise for our society. Due to this fact, the next generation of students will need more educational training in this area, especially for those students engaged in engineering and technology programs. In this study, an interactive, industrial-component-based bench unit was developed as an educational tool for two different configurations of electric drivetrains: battery-electric and series-hybrid electric. The unit is capable of demonstrating, illustrating and displaying multiple energy flows in the electric-drive vehicle, based on its configuration and driving conditions. The integrated unit provides students with practical, hands-on experiences that favor typical learning styles, encouraging students to learn by doing.

The implementation of the electric-drivetrain bench unit was a resounding success and initial student reaction was quite enthusiastic. The hands-on experience not only enhances their vehicle electrification training and education, but also inspires multidisciplinary students to become interested in the green movement of transportation. For safety concerns, the current bench is powered by a low–voltage, 12V lead-acid automobile battery, though there are plans to upgrade it in the future to other types of battery chemistries such as NiMH or Li-Ion. The development of the second bench unit is ongoing.

Acknowledgements

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