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INCORPORATING SYSTEMS ENGINEERING INTO THE SENIOR DESIGN – AUTONOMOUS LAWN MOWING MACHINE

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1. INTRODUCTION

Systems Engineering is an interdisciplinary process that ensures the satisfaction of customer's needs throughout a system's entire life cycle. The purpose of systems engineering is to produce systems that satisfy the customers' needs, increase the probability of system success, reduce risk and the total life-cycle cost. This process consists of seven tasks with the acronym SIMILAR (Bahill, 1998) as shown in Figure 1.

Figure 1. The Systems Engineering Process

1.1 State the Problem.

Stating the problem is the most important systems engineering task. It entails identifying customers, understanding customer needs, establishing the need for change, discovering requirements and defining system functions.

The problem statement starts with a description of the top-level function which the system must perform or the deficiency that must be ameliorated. It includes system requirements stated in terms of what must be done, not how to do it. It might be composed in words or as a model. Inputs come from end users, operators, bill payers, owners, regulatory agencies, victims, sponsors, marketing, manufacturing, etc. These are called stakeholders. Identifying the stakeholders is an important initial task. In a modern business environment, the problem statement starts with a reason for change followed by vision and mission statements for the company. The problem statement is one of Systems Engineering's most important products. An elegant solution to the wrong problem is less than worthless.

1.2. Investigate alternatives.

Alternatives are investigated and evaluated based on performance, cost and risk.

Alternative designs are evaluated based on performance, cost, schedule and risk criteria. No design is likely to be best on all criteria, so multi-criteria decision aiding techniques should be used to reveal the preferred alternatives. This analysis should be redone whenever more data are available. For example, criteria should be computed initially based on estimates by the design engineers. Then models should be constructed and evaluated. Next simulation data should be derived. Subsequently prototypes should be measured and finally tests should be run on the real system. For the design of complex systems, study of alternative designs reduces project risk. Investigating bizarre alternatives helps clarify the problem statement. This is one of the main processes used to define system architecture.

1.3 Model the system.

Running models clarifies requirements, reveals bottlenecks and fragmented activities, reduces cost and exposes duplication of efforts.

Models will be developed for most alternative designs. The model for the preferred alternative will be expanded and used to help manage the system throughout its entire life cycle. Many types of system models are used, such as physical analogies, analytic equations, state machines, block diagrams, functional flow diagrams, object-oriented models, computer simulations and mental models. Systems Engineering is responsible for creating a product and also a process for producing it. So, models should be constructed for both the product and the process. Process models allow us, for example, to study scheduling changes, create dynamic PERT charts and perform sensitivity analyses to show the effects of delaying or accelerating certain subprojects. Running the process models reveals bottlenecks and fragmented activities, reduces cost and exposes duplication of effort. Product models help explain the system. These models are also used in trade-off studies and risk management.

1.4. Integrate.

Integration means designing interfaces and bringing system elements together so they work as a whole. This requires extensive communication and coordination.

Integration means bringing things together so they work as a whole. System integration means bringing subsystems together to produce the desired result and ensure that the subsystems will interact to satisfy the customer's needs. End users and engineers need to be taught to use the system with courses, manuals and training on the prototypes.

1.5 Launch the system.

Launching the system means running the system and producing outputs -- making the system do what it was intended to do.

Configuration management (also called modification management) ensures that any changes in requirements, design or implementation are controlled, carefully identified, and accurately recorded. All stakeholders should have an opportunity to comment on proposed changes. Decisions to adopt a change must be captured in a baseline database. This baseline is a time frozen design containing requirements for functions, performance, interfaces, verification, testing, cost, etc. Baselines can only be changed at specified points in the life cycle. All concerned parties must be notified of changes to ensure that they are all working on the same design.

1.6 Assess performance.

Performance is assessed using evaluation criteria, technical performance measures and measures -- measurement is the key. If you cannot measure it, you cannot control it. If you cannot control it, you cannot improve it.

During the operation and maintenance phase of the system life cycle the performance of the system must be measured. Initially these measurements will be used to verify that the system is in compliance with its requirements. Later they will be used to detect deterioration and initiate maintenance.

*1.7 R**e**-evaluation.*

Re-evaluation should be a continual and iterative process with many parallel loops.

Re-evaluation is arguably the most important task of Systems Engineering. For centuries engineers have used feedback to control systems and improve performance. It is one of the most fundamental engineering tools. Re-evaluation means observing outputs and using this information to modify the system inputs, the product or the process. Re-evaluation should be a continual process with many parallel loops. Everyone should continually re-evaluate the system looking for ways to improve quality.

In the Department of Engineering at Indiana University Purdue University Fort Wayne, the Capstone Senior Design (SD) spans two semesters. In the first semester, students write the problem statements which include system requirements, specification, and design variables, brainstorming various design options, generate concept designs, evaluate the conceptual designs and finish their detailed design. In the second semester, students implement and build their detailed design, test and evaluate their prototype. Besides the assessments from Industrial Sponsors, faculty members, enrolled students, SD course coordinators and Senior Design faculty advisors, several Systems Engineering reviews are also conducted, which include System Requirement Review (SRR), Preliminary Design Review (PDR) and Critical Design Review (CDR). The SD process is shown in Figure 2.

Figure 2. Senior Design Process at IPFW

In this paper, the SD experience integration with Systems Engineering in one project – Autonomous Lawn Mowing Machine is presented. This approach has been proven to be every effective in improving students' recognition of the methodologies and strategies of system engineering approach in their major fields.

Autonomous Lawn Mowing Machine project is a multi-disciplinary SD project which involves Electrical and Computer Engineering (ECE) students together with Mechanical Engineering (ME) students. This project is targeted to be as the first stage in participation of ION Robotic Lawnmower Competition sponsored by the Institute of Navigation (ICON, 2009). ECE/ME students work together as a team and they design, build and test the prototype in two semesters.

2. PROBLEM STATEMENT

This is S-stage in "SIMILAR" system engineering – state the problem. During this stage, students understand the needs, discover the system requirements and specification, establish the design variables (software and hardware) and desirable design objectives, understand the limitations and constraints.

Our objective of this SD project is to improve the navigation of the mower by using a systematic mowing pattern and to develop a prototype and experiment to measure the improvement. The tentative target is to design and build an autonomous lawn mower that can successfully mow at least 75% of a 20 ft by 20 ft area. This percentage was chosen to match the specifications in the 2009 ION Robotic Lawnmower Competition. Under the normal conditions, the mower will travel along a straight line until a boundary is reached. At this point the mower will turn around and continue along a path that is parallel and adjacent to the previous pass as shown in Figure 3.

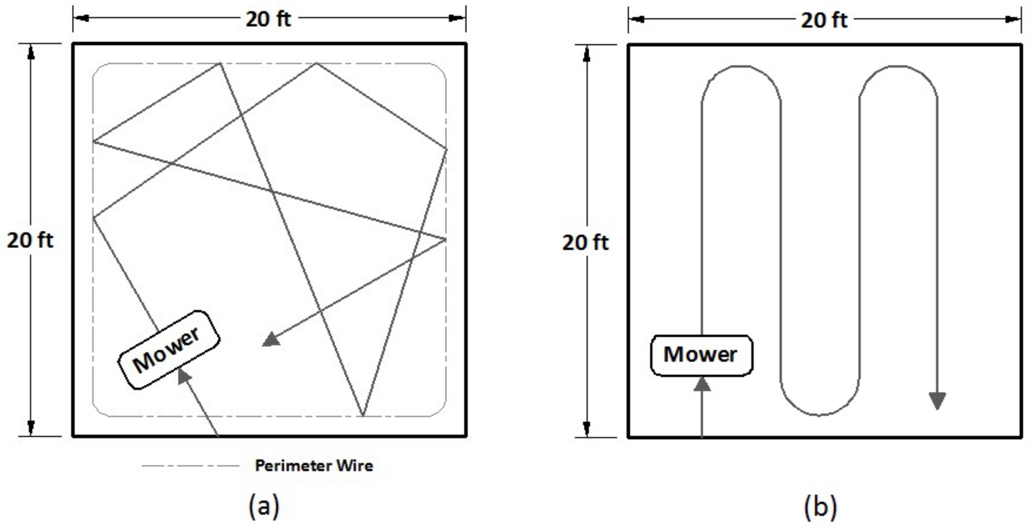

Figure 3 Comparison of the mowing paths for (a) commercial mowers and (b) proposed design

Some other design objectives are 1) the design cost is below a certain amount, 2) the design system requires to be fixed in a certain space, 3) the design system is able to be expanded for future SD projects.

3. SYSTEM REQUIREMENT REVIEW (SRR)

During the SRR, faculty members and project advisors assess the completeness and suitability of the problem statement and resulting set of requirements which quantify the problem definition. This review is carried out in the form of oral presentation by each design team of their problem statement. The oral presentations are scheduled during the weekly common meeting by the coordinator. Advisors must attend the presentation of his/her design team. Faculty members are encouraged to attend and participate in the review.

4. BRAINSTORMING AND CONCEPTUAL DESIGNS

This is the I-stage in “SIMILAR”. During this stage, students envision the basic structure and essential components of an autonomous mower, identify the essential systems such as drive, sensors, controls, navigation, and grass cutting power, brainstorm many possible solutions to each essential system, analyse each concept for feasibility and identify potential problems and design criteria, compare and do further research of these designs, etc. For example, Table 1 shows the comparison of one essential component - cutting power plants.

Through brainstorming ideas, students come with several conceptual designs. They compare the pros and cons of each design, take other factors such as donated parts, available components into consideration and come with a final solution and a backup solution. Among the three conceptual designs, Electric Drive and Electric Cutting with Battery Power, Electric Drive and Gasoline Cutting with Laser Perimeter Guides, and Electric Wheelchair Drive with 4 Cycle Gasoline Engine and Alternator, through comparisons of advantages and disadvantages, the “Electric Wheelchair Drive with 4 Cycle Gasoline Engine and Alternator” is chosen to be the final design and the “Electric Drive and Electric Cutting with Battery Power” as the backup.

Table 1: Comparison of Cutting Power Plants

	2-cycle	4-cycle	Electric
Parts	Some moving parts	More moving parts	Few moving parts
Maintenance	Low	Must change oil	Low
Storage	No special requirements	Must keep level	No special requirements
Vibration	Some vibration	Higher vibration	Little vibration
Fuel Economy	Less efficient	More efficient	N/A
Emissions	Burns oil with gasoline	Gasoline exhaust	None
Torque	Less potential	More potential	More potential
Starting	Easy	Harder	Effortless
Weight	Light	Heaviest	Light

5. PRELIMINARY DESIGN REVIEW (PDR)

During the PDR, faculty members and project advisors assess the selected conceptual design to confirm that the design approach satisfies the requirements, risks are under control and that the preliminary design is ready to be detailed. This review will be carried out in the form of oral presentation by each design team of their selected conceptual design. The oral presentations will be scheduled during the weekly common meeting by the coordinator. Advisors must attend the presentation of his/her design team. Faculty members are encouraged to attend and participate in the review.

6. DETAILED DESIGN

This is the 2nd I-stage in “SIMILAR”. During this process, students pick up each component for mechanical and electrical designs such as, driver motors, drive wheels, brackets, shaft encoder adapter, mower and engines, microcontrollers, switch regulators, batteries, digital compass, shaft encoders, microcontrollers, etc. They also draw the CAD design, write the flowchart of software design, schematic of hardware design, and run the simulations. After that, they also perform the cost analysis to make sure the budget requirement is met.

7. CRITICAL REQUIREMENT REVIEW (CRR)

For the CRR, students present their final detailed design to the faculty and industrial sponsors. Feedback/responses will be taken into count in the implementation stage. In some cases, redesign some parts could be conducted.

8. IMPLEMENTATION

This is the L-stage in “SIMILAR”. During this process, student build the prototype of Autonomous Law Mowing Machine, which include lawn mower deck, mounting bracket, drive motors, driving wheels assembly, batteries and bumper system implementation and installation, proximity sensor installation, microcontroller wire connections, shaft encoder and limit switches installation, installation of digital compass and emergency stop button, software writing. A picture of the finished prototype is shown in Figure 4 and Figure 5 describes the flowchart of software design.

Figure 4. Lawn Mowing Machine Picture Shot

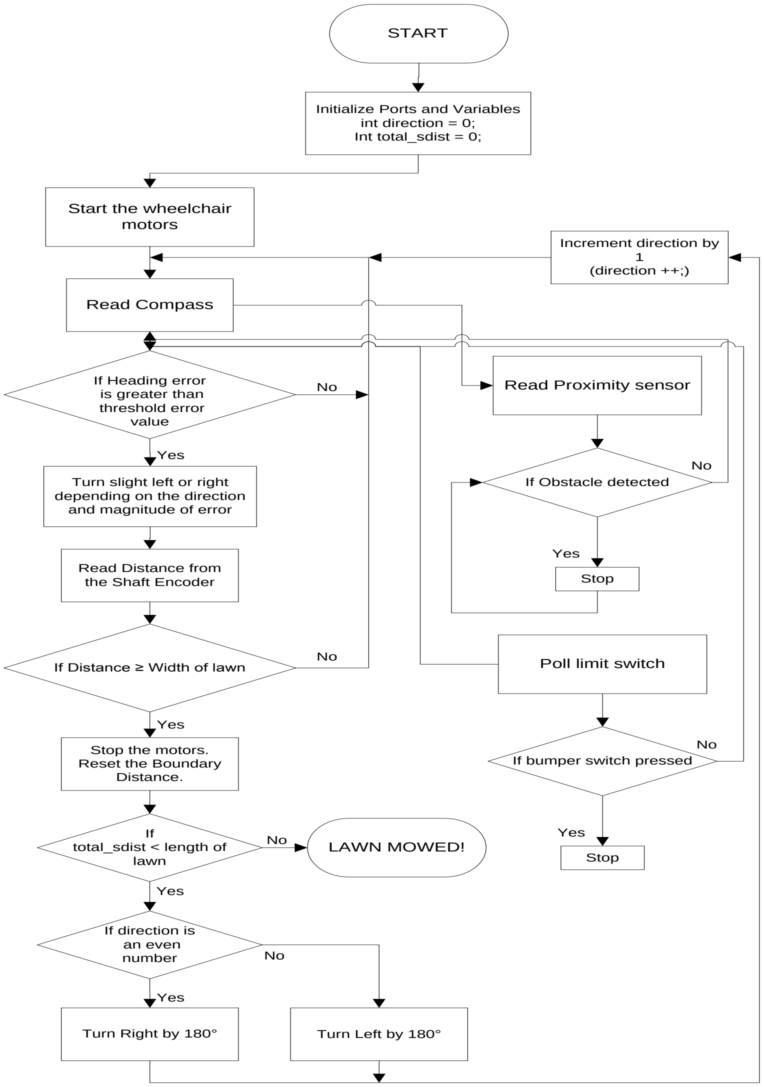

Figure 5. Flowchart of Software Design

9. TESTING/EVALUATION

This is the A-stage in “SIMILAR”. During this process, student measure parameters to make sure the designs meet design requirements. The following parameters are measured which include electrical and mechanical ones.

Electrical Parameters:

- **Requirement:** The mower must be able to make 180 degree turns.
  Parameter measured: Turn Angle

- **Requirement:** The mower must be able to travel in a straight path using compass.
  Parameter measured: Lateral displacement

- **Requirement:** The shaft encoder must be used to determine the distance travelled to determine the boundary.
  Parameter measured: Distance travelled

- **Requirement:** The mower must use the proximity sensor to detect obstacles and stop to avoid collision.
  Parameter measured: Distance at which it detects obstacles and stops

Mechanical Parameters:

- **Motor stall torque:** The motor stall torque could not be determined by the manufacturer of the motors. This specification had to be measured.

- **Bumper system spring stiffness:** The bumpers once depressed were returned to the normal operating position by springs. These springs were purchased from a local hardware store so their spring constant was not known. The spring constant was determined by deflecting the spring a measured distance and using a scale determined the force required to deflect the spring that distance. This was done several times with different deflection distances and averaged. The spring constant was determined to be 7 lbs./in.

- **Mower weight:** The mower's total weight was difficult to directly measure, due to its size and no scale large enough to hold the entire mower at one time. Therefore, each wheel's reaction force was measure and then summed. The reaction force was measured using a bathroom scale at each wheel, while using books at the other wheels' locations to keep the mower level. The total weight was 160 lbs.

Besides running these tests through programmed software and implemented hardware, students also perform mechanical analysis such as drive motor analysis, bumper system analysis, motor key analysis, drive plate Finite Element analysis, etc. and make sure they meet the desired objects.

10. RE-EVALUATION

The evaluations have been integrated through the whole process of SD experience through SDR, PDR, and CDR. Students, faculty members, industrial sponsors provide response/suggestions to the whole process.

11. SUMMARY

The integration of System engineering approach in the SD projects has provided students an excellent opportunity to the recognition of the methodologies and strategies of system engineering approach in their major fields. This approach can prepare students better in their future career after graduation.

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