AC 2012-4719: INTEGRATING AEROSPACE RESEARCH MATERIALS INTO A PROJECT-BASED FIRST-YEAR ENGINEERING DESIGN COURSE

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Integrating Aerospace Research Materials into a Project-Based First-Year Engineering Design Course

Abstract

Faculty members at Texas A&M University have made significant strides in using project-based learning in first-year engineering courses to promote understanding of mathematics and science and the practice of engineering. Project specifications developed and utilized for the last seven years ensure students use mathematics and science concepts in the engineering process of design and modeling to make performance predictions prior to the build and then use the build to obtain verified results.

Seeking to excite freshman students about aerospace materials science applications in the first-year, faculty members and graduate students in the Aerospace Engineering department at Texas A&M University developed projects involving shape memory alloys (SMAs), which utilize the shape memory effect for shape and actuation control applications. By introducing projects using SMAs, students learn about their applications, their relationship to the aerospace field, and the potential for material science as a future research goal. This paper will expand on the work published in the proceedings of the 2011 ASEE Conference and Exposition[1]. Through the use of SMAs and standard Lego Mindstorm kits, the project involves students building and programming a Mars-rover type Lego robot to accomplish a mission. In keeping with the aerospace theme, a lightweight material is optimally preferred and central to actuating un-inhabited autonomous vehicle, (i.e., the robot's claw in lieu of a motor-driven claw). This paper will present specifications for the project developed using SMAs, provide details on the implementation and integration of aerospace materials with engineering design and visual programming, and summarize the results of the project.

Introduction

Texas A&M University (TAMU) converted their two freshman engineering courses into a project-based format centered on engineering design several years ago[2,3]. This project-based format provides incoming freshmen their first hands-on view of the engineering design process. However, most of the design projects have not utilized engineering designs that are more directly related to aerospace engineering until recently[1]. The work published in the 2011 ASEE Conference and Exposition detailed the incorporation of an aerospace-related project in the first semester[1]. We have extended this work into the second semester course of this two-semester freshman engineering sequence to incorporate a project using aerospace engineering materials. The use of aerospace materials is introduced in a manner that is in keeping to the second semester's approach, which is to tie in introduction to basic time and project management, flowcharting, and visual programming to the project-based engineering design format. The programming component has always been a principal theme of the second semester. The design project is to build and program an un-inhabited autonomous vehicle (UAV), a LEGO® Mindstorm® robot, for a mission. The UAV/robot's mission is to find an empty can of soda, pick it up, find its path, and follow it through a tunnel, while avoiding obstacles to deliver the can to a final destination (Appendix 1). Rather than use a motor to actuate the claw that grabs the can, a shape memory alloy (SMA) “muscle” wire is used to open the claw to grab the can. The advantage here is that less energy is required for a lighter setup. One gram of 100-micron diameter SMA wire can elevate up to two orders of magnitude times its weight when it contracts subjected to electro-thermal excitation[4].

The mission of the robot in the second-semester course depends upon whether the robot is moving toxic waste (a more civil engineering majors’ theme) or a Mars rover (a more aerospace engineering majors’ theme). Naming it a Mars rover does not make the project aerospace-centered, nor does building the robot to resemble a Mars rover. That would not be sufficient to impress the modern incoming freshman-engineering student. Students recognize the fact that a mission to Mars has to be lightweight to avoid using a lot of fuel to get there. It also has to stay within a minimal use energy budget given the lifetime of batteries, fuel cells or even size of nuclear power sources or availability of sunlight for solar panels. These typical aerospace engineering requirements validate the use of aerospace engineering materials in the project.

In this paper, we seek to chronicle the experience of introducing SMA wires into a robot design project in the second part of a two-semester sequence. The next section of the paper covers the background of the course followed by a section describing the project. The third section then details the implementation of incorporating SMA wires into the robot designs. The fourth section analyzes the results of the various student teams’ designs and the student assessment of the integration of SMA wires into the project. Lastly, we summarize the work and conclusions with projections for future use.

Background

First-year engineering courses provide students with their first view of engineering. These first courses historically have focused on ensuring that students learn the mathematics and science needed for follow-on courses and have not emphasized the engineering use of these basics at this stage. This has left students wondering what the basics have to do with their major, if they selected the right major, if engineering will keep their interest, etc. The project-centered approach that TAMU implemented has improved student attitude and first-year retention[2], but the projects have not covered as many different fields of engineering as the course designers’ desired. The course designers have always sought project ideas, considering that students from different majors are typically assembled in interdisciplinary teams of four. Recent work with projects sought to broaden the range of engineering fields to include aerospace materials[1].

As with all freshman-engineering projects, the project had to meet the same requirements, including: project must address societal need; students will predict performance of the design using mathematics and science principles; and project supports the engineering process[2]. The use of SMA wires in this project was introduced in a manner as to require minimal changes in the project plan. In fact, the project description given to the students (as a “work request” or “request for proposal”, etc.) did not specify how the claw was to operate. The SMAs have been incorporated into the second-semester freshman engineering course for two semesters. In the spring of 2011, students were given the option of using the SMA wires, and most did. In the fall of 2011, students were required to use SMA wires in their project design.

The elements the projects must contain are summarized in the table below. The third column shows where influences of this new project enter.

ELEMENT	REASONING	ADDED
Needs Identification	What is to be accomplished?	What if weight was important? A constraint? Budgeted?
Conceptual Design	How might the need be met? What alternatives should be considered?	Consider “lighter” option
Analysis and Modeling	What is involved in determining whether the conceptual design will meet the need? Technically feasible? Can it be modeled mathematically?	Quantifying and calibrating materials used (e.g., amount of SMA contraction)
Verifying and Assessing	Can the predictive models be validated through physical testing?	Computing and assessing loads, any mechanisms, gears, levers, etc.

Project Summary

Course Details

At the start of the semester, multidisciplinary teams of four students are formed in the class by grouping students from different sections and majors at TAMU. Students then work together in their teams during class on a daily basis and outside of class as well. This is a necessary part of the second semester course since much of the time is spent building and programming the robot rather than formal lecturing. The hands-on design focus dictates minimal lecturing and more critical thinking to figure out how to make the robot accomplish each task. Because many of the students in each team are taking the same first-year core-curriculum mathematics and physics courses, students can form study groups to work on their projects outside of class and to assist each other with courses, other than this one.

The instructors for this course include a problem-solving instructor and a graphics instructor. Included in the course management structure are a teaching assistant, usually a graduate student, and a peer teacher, usually an undergraduate student who recently completed the freshman-engineering sequence. The graphics portion of the class has the students use a commercial graphics package that can be used to draw parts selected from outside of class or parts of their robot by the end of the semester. At the beginning of the semester, basic project planning is covered as well as an introduction of flowcharting and some basics of the visual programming environment, in this case LabView. The most important aspect of the programming portion is actually what the program is being asked to do and how it completes the task. Since LabView is many times not the programming language of choice in the student’s follow-on curriculum, defining the structure and purpose of the program through flowcharting is applicable to a variety of structured programming languages the student will encounter. Therefore, this is emphasized in the class. Nevertheless, each team is given access to a LabView manual for the class[5].

Grading is based mostly on individual work shown through understanding of elements of flowcharting on homework and exams. Most of the experiential learning that develops arises from working on the projects, which includes programming the robot, i.e., from writing code similar to writing an essay from a new language being learned in class. This writing analogy also explains why no two teams have the same exact code and not simply differ on the types and numbers of sensors chosen for use. The project grades are generally based on the team as a whole. However, team evaluations are accounted in the final project grade when, inevitably, conflicts arise in a few teams and some team members do more work than others.

While the mission of the robot is to find a payload (represented as a soda can) and navigate a path to a destination, the mission is sub-tasked into parts to be accomplished at different times during the semester. A brief project report memo is usually due at different times during the semester from the team on each sub-task accomplished to keep students on track.

In the first two weeks, students calibrate the different sensors that come with the robot. These include:

1. The light sensor to quantify what percentage of reflected light from a color of tape, table, or floor corresponds to a color;
2. The motor rotation angle turned to the distance traveled by the robot based on the chosen wheels and configuration;
3. The ultrasound sensor to measure distance to an object;
4. The sound sensor to gauge response to sounds;
5. The touch sensor to show “true” if touched vs. “false” if not.

The next two weeks are spent by students programming the robot to follow a line of blue tape using the light sensors without straying. The robot must do this without being confused when it goes through a tunnel where the light changes.

In the following two weeks, students program the robot to avoid obstacles. The difficulty here is to not program the robot for too specific of an obstacle size.

During the remainder of the class, students combine all of these subtasks into one code for the entire mission. This is interspersed with learning engineering drawing using a commercial graphics package throughout the semester.

Revision to Robot Project

To integrate the SMA wires into the robot design project while keeping changes to a minimum, the only change incorporated was the use of SMA wires to actuate the robot claw. This minimal change made it easier to integrate into the existing course structure without rewriting the entire project description or tempering with pedagogy.

The required method for actuating the robot claw employed the uniaxial contraction of Nitinol SMA wire via thermally induced transformation. Therefore, the electric motors that come packaged with the provided LEGO kits are explicitly banned from use for the claw, but other motors may be used for the robot wheels. Each team is provided 100 cm of SMA wire from MuscleWire, a provider of commercially available Nitinol wires to study, test, and integrate into their claw designs[6]. For reference, each meter of low-temperature, 150 µm diameter SMA wire costs $18.95, as of October 2010[6]. For this project, 15 meters are ordered for distribution over 24 teams, totaling approximately $285 for the class. Excess wire is provided for those teams that request it in the event of burnout, breaking, or loss.

After the first six weeks of the semester, the SMA is introduced to the students. They are given a brief background on the material and a series of procedures for quantifying and calibrating the wire contraction[1].

After the introduction and calibration of the SMA wires, students are given a class on gears, so they can figure out what combination of gears, along with some lever arm, will amplify the wire contraction to achieve the desired claw opening to grab an empty can of soda. The SMA wires must be pre-loaded, so rubber bands keep the claw closed until an electrical signal heats the wire to contraction. Within a few seconds, SMA wire can contract to over 20% of its original length[4].

Implementation

Calibration

Calibration of the SMA wires was previously discussed in the proceedings published in the 2011 work[1]. The quantification of actual wire contraction for duration of connection to battery terminals has no bearing on this different application. Figure 1 shows SMA wire being tested for quantifying specific correlated contraction with a chosen length based on where the alligator clips connect to a 6V battery's terminals.

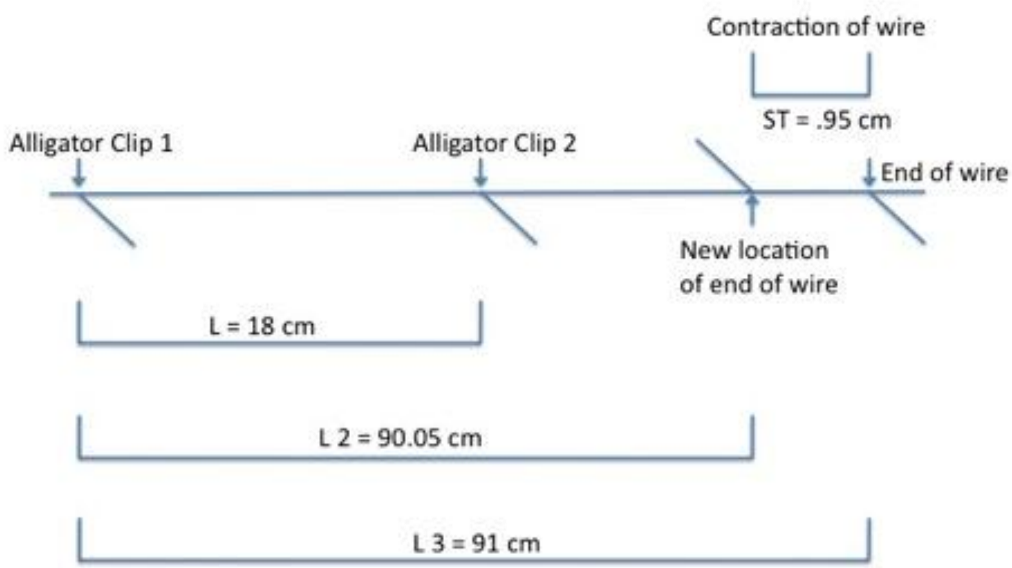


Figure 1. Analyzing the SMA wire.

Gearing

While some student teams try different gears from the Lego kit for different vehicle wheels or bulldozer track chains, most have not seen an actual introduction to gears in their physics course yet. Some may have seen it in the previous semester freshman-engineering course if they were enrolled in the section that used SMA wires in one of the projects. Therefore, to provide a baseline a brief introduction to gears is given to the class. The instructor demonstrates a robot claw design using gears and a lever arm to illustrate the magnification of the angular displacement of the claw or opening to a certain percentage of SMA wire contraction.

The following contains the gear design for the SMA wire as reported by one of the teams.

> "SMA wire contraction was approximately 0.65 cm. For the claw design, gear sizes were as follows: d1 = 5 cm; d2 = 3 cm; d3 = 1 cm.
> For the relation of the gears: d1/d2 = 5/3; d2/d3 = 3; G1,3 = (5/3)*3 = 5.
> Therefore, contraction = h and angular displacement = θ, so h = d*θ. For gear one, $\theta = 0.65/(0.25) = 0.26$, or approximately $\pi/12$ radians. Since the relationship between gears one and three is based on proportion 5, the smaller gear at the end near the claw rotates approximately $5\pi/12$ radians[7]."

This approximate 90-degree opening was more than enough to grab the can.

Integrating into Design

Connecting the robot claw assembly to the rest of the vehicle was straightforward. The longer length of wire deemed necessary by a team meant more routing of wires around the vehicle using pulleys as needed. Figures 2 – 4 show various robot designs and different connections of SMA wires to the robots.

The program that renders the vehicle autonomous is coded on a computer using the LabView graphical visual programming environment and then downloaded via a USB cable to the Lego's NXT brick housing in the robot's central processing unit (CPU). Sample flowcharts for two different actions are in Appendix 2 and Appendix 3. Sample codes are contained in Appendix 4.

A "Timed Motor" pre-programmed routine in LabView provided the software link to send the current to the wire. While a 6V battery was used to test the wires, CPU and battery pack had up to 9V available. This was more than enough for the wires. The CPU did not get any feedback, nor did it need to do so, to know that it was really actuating SMA wires instead of a motor.

The teams created with many imaginative UAV/robot designs. Some teams did not use a claw at all but used the SMA wires to activate a release mechanism to drop a gate onto and around the can and keep it enclosed throughout the rest of the robot's mission (Figure 4).

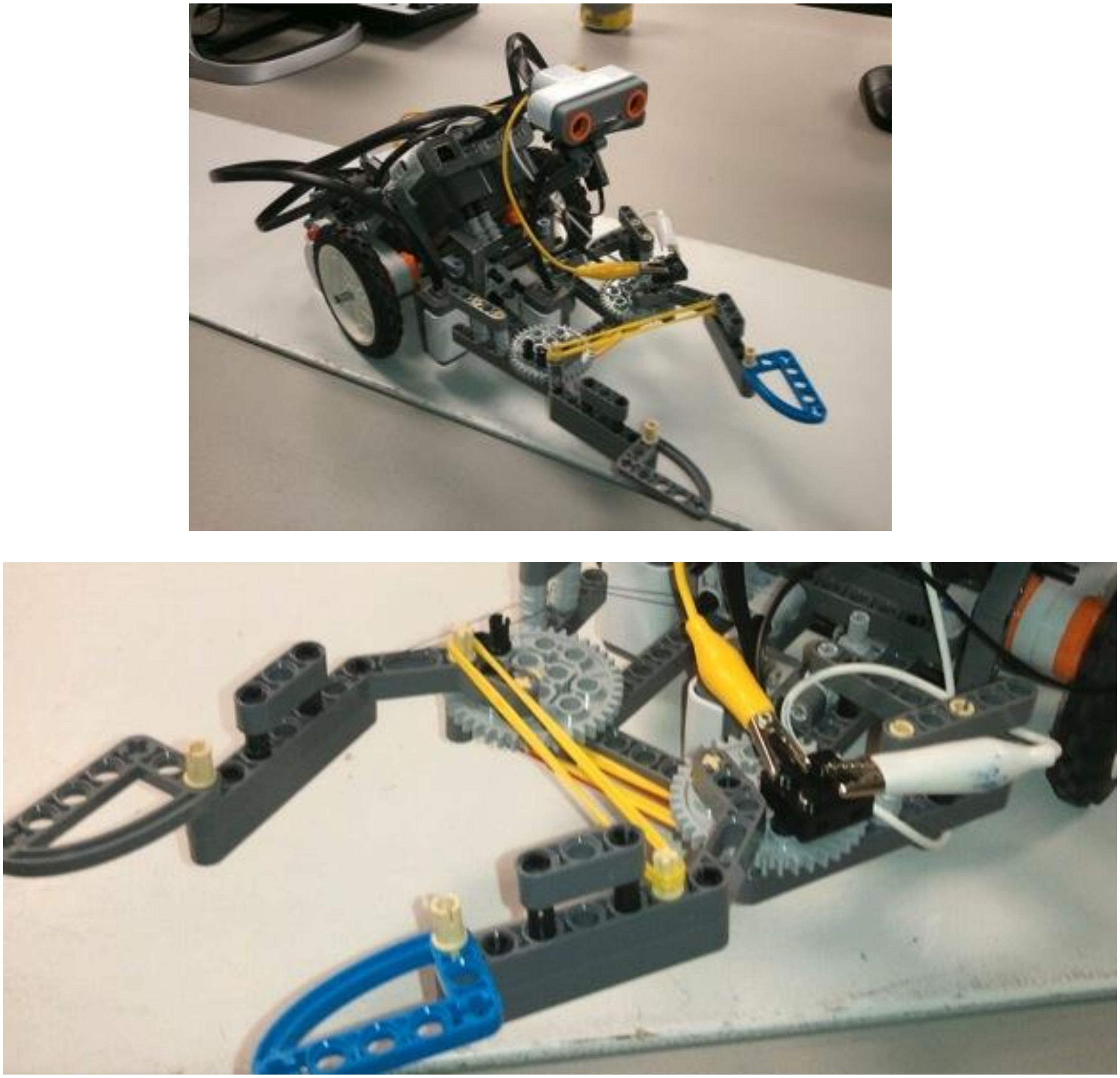


Figure 2. Sample UAV/robot claw design and SMA wire connection.

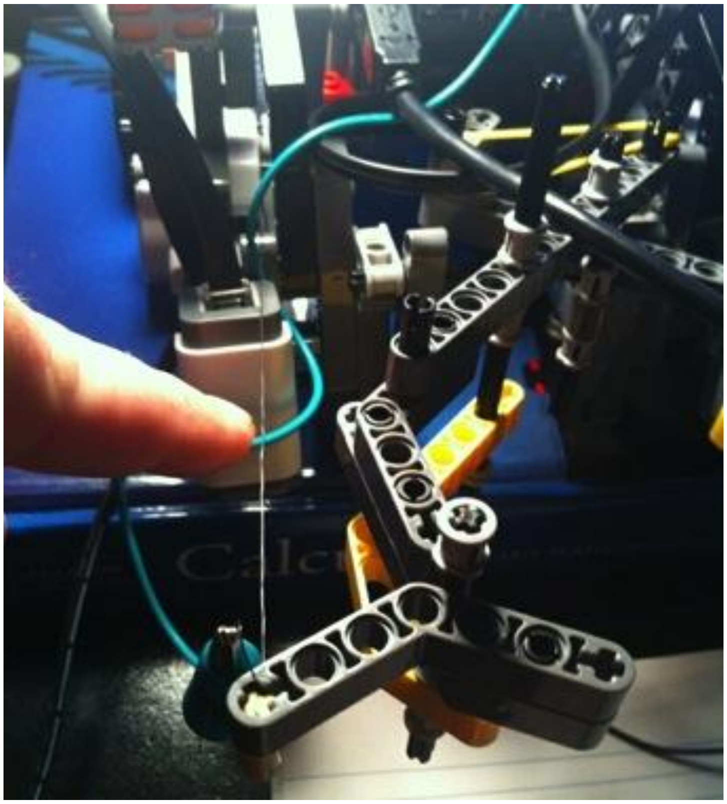


Figure 3. Note placement of SMA wire in one UAV/robot claw design.

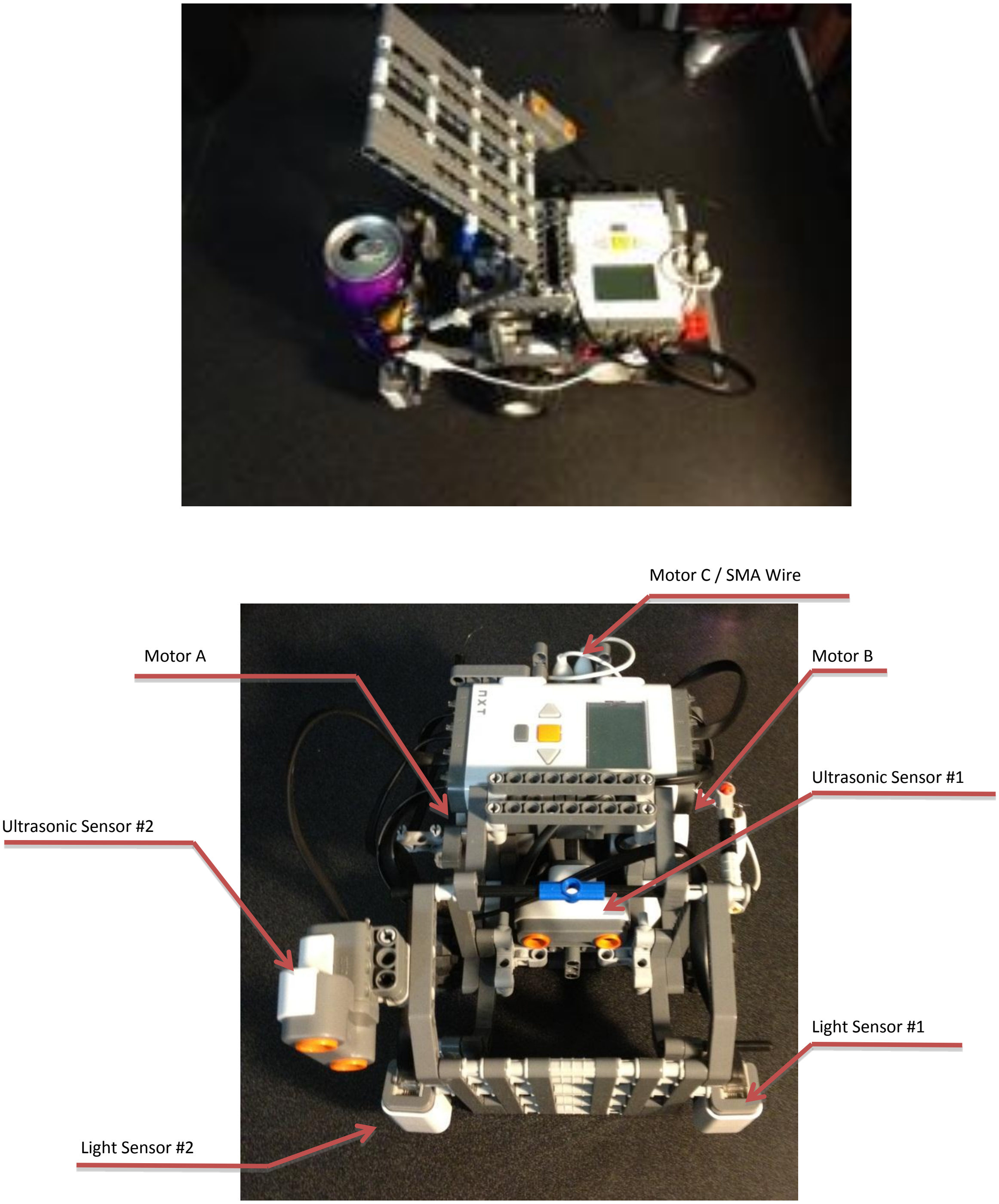


Figure 4. Robot and gate design.

Results

The following are excerpts from students' final reports on the project. Figures 1 – 5 and Appendix 1 and Appendix 2 are excerpts from student reports[7]. Note in Figure 5 how one team internalized key elements of the design process: "The diagram shows the thought process we used to create our robot[7]."

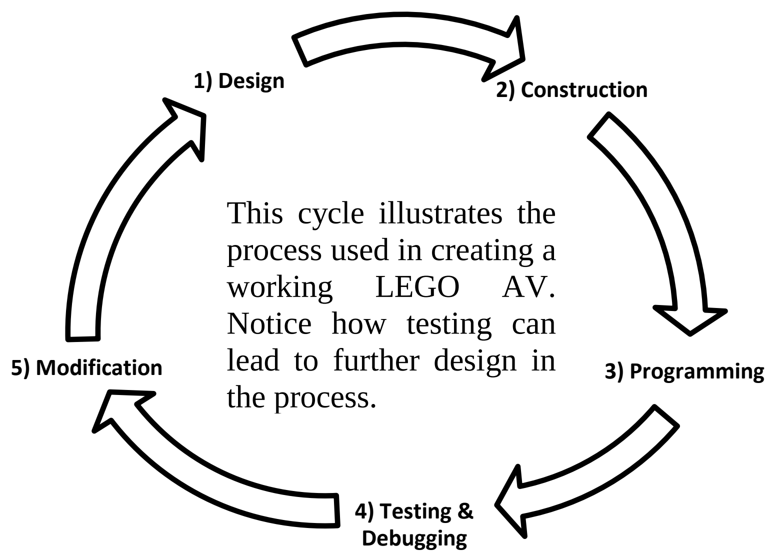


Figure 5. UAV design process described by a student team.

The SMA wires themselves varied in the amount of contraction. One team found 10" of SMA wire contracted 3/8" within one second of being heated. While SMA wires are rated as being able to contract as much as 20%, some teams only found as little as 1%. As a result, fitting the SMA wires themselves onto the robots was not as much of a problem as trying to get the right number of gears or levers to amplify the displacement of the wire. Incorporating the SMA wires into the code was simple as it replaced a third motor in the code in most cases.

After checking the SMA wires one "team set up a claw mechanism with the wire and three differing gears. Manipulating gear placement within the mechanical design, the claw eventually managed to meet a 45-degree requirement upon opening due to the SMA wire's contraction and the angular gear relationships built into the claw. The mathematics of the proportions of the gear sizes also correlated nicely with the observed performance trials[7]."

One team found insufficient contraction for a claw design. No matter what gears they used, they were only getting 3%-5% contraction. Therefore, changing to a gate design turned out to be an engineering breakthrough for the team. "To activate the gate, we attached a lever arm at its pivot point. We found the longer the lever arm, the less force was required of the SMA wire. These gate ideas worked very well as it used a simple lever arm instead of gears and used gravity to help finish its operation[7].” Only one team was never really able to incorporate the SMA wires.

At the end of the semester, students completed a survey with specific questions addressing the SMA project used in the course. The survey results are presented in Table 1 and Table 2. As shown in Table 1, the use of SMA wires in the project did not motivate students to learn more on multi-functional materials with a large percentage of students feeling the incorporation of SMAs needed improvement. There is also a mixed review from students when asked if the project should be used in future second-semester freshman engineering courses. Again, some work needs to be done in the next implementation. Table 2 shows results by the students of their learning of engineering concepts. The main intent of the course is to impart an understanding of engineering design to incoming freshman engineering students. The majority of the semester is spent working on this project and utilizing SMAs in the design. The results show the majority of students agreed that their level of understanding increased. Comments received from students indicate that including SMA wires in the project was beneficial. Comments from students included: “Use of SMA made the project more complex but added a dimension that made the project cool, and SMA is a good concept but very difficult to implement”.

Table 1. Assessment of SMA use in class.

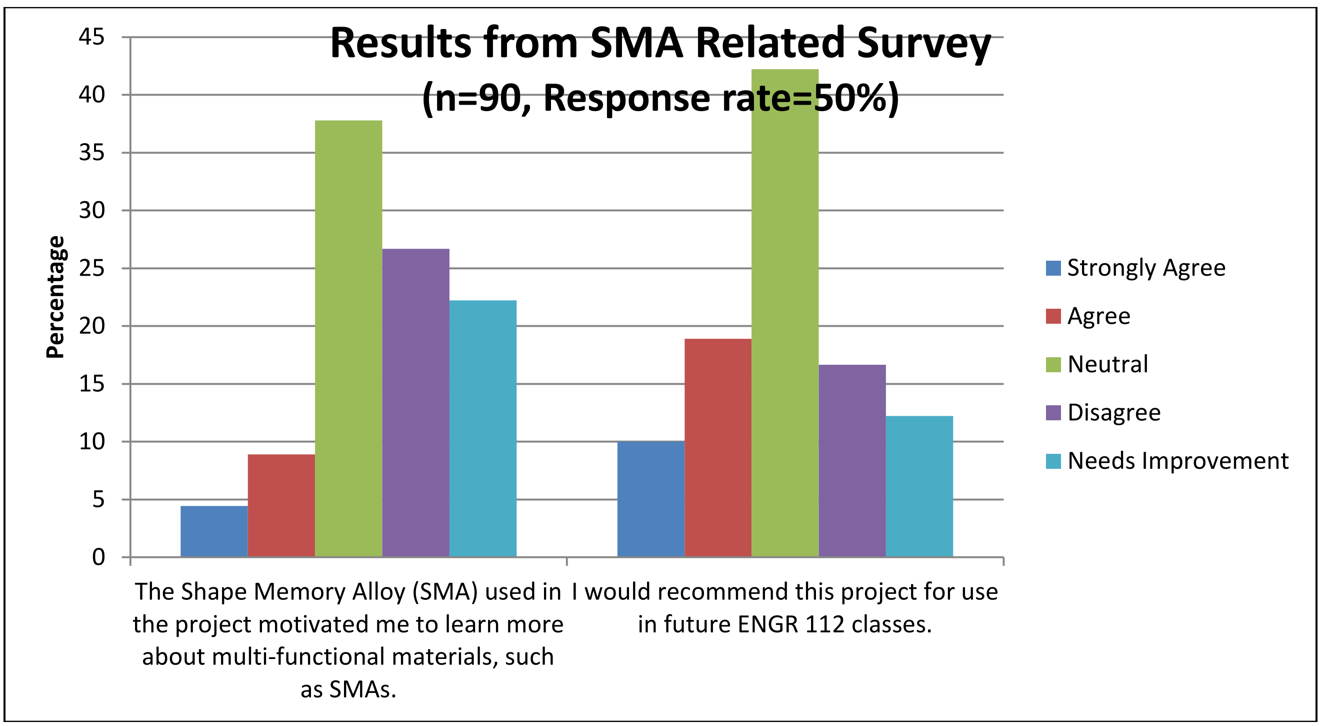
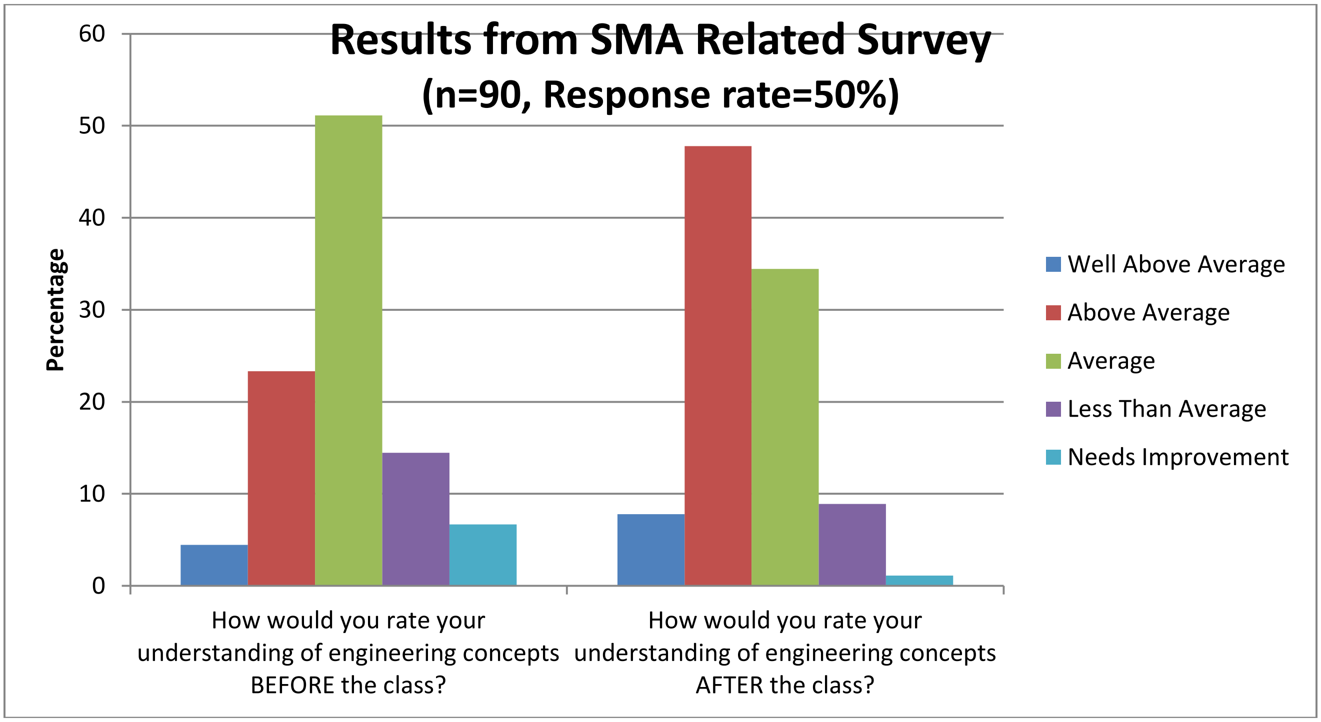


Table 2. Continuation of assessment of SMA use in class.



Summary and Conclusion

The students presented outstanding projects. In all of the final reports, students expressed having learned a lot about the engineering design process. Flowcharting and coding in the graphical visual programming environment were new to the students, but once they learned this, programming the SMA wire operation into the robot code was simple as it just replaced another motor. Frustration was felt by students trying to amplify small displacements of the SMA wires in their quest to actuate a robot claw or gate mechanism. Overall, students' comments suggested increased learning of engineering design and using problem solving. With this being the first full-scale implementation of SMA wires into the particular project, further work will need to be done to excite students to learn more about aerospace materials science applications, which was a goal of this work.

The broader impact was in the lessons learned on how students evaluated their design, made adjustments, and retested. That was one of the most important lesson students learned in engineering design.

References

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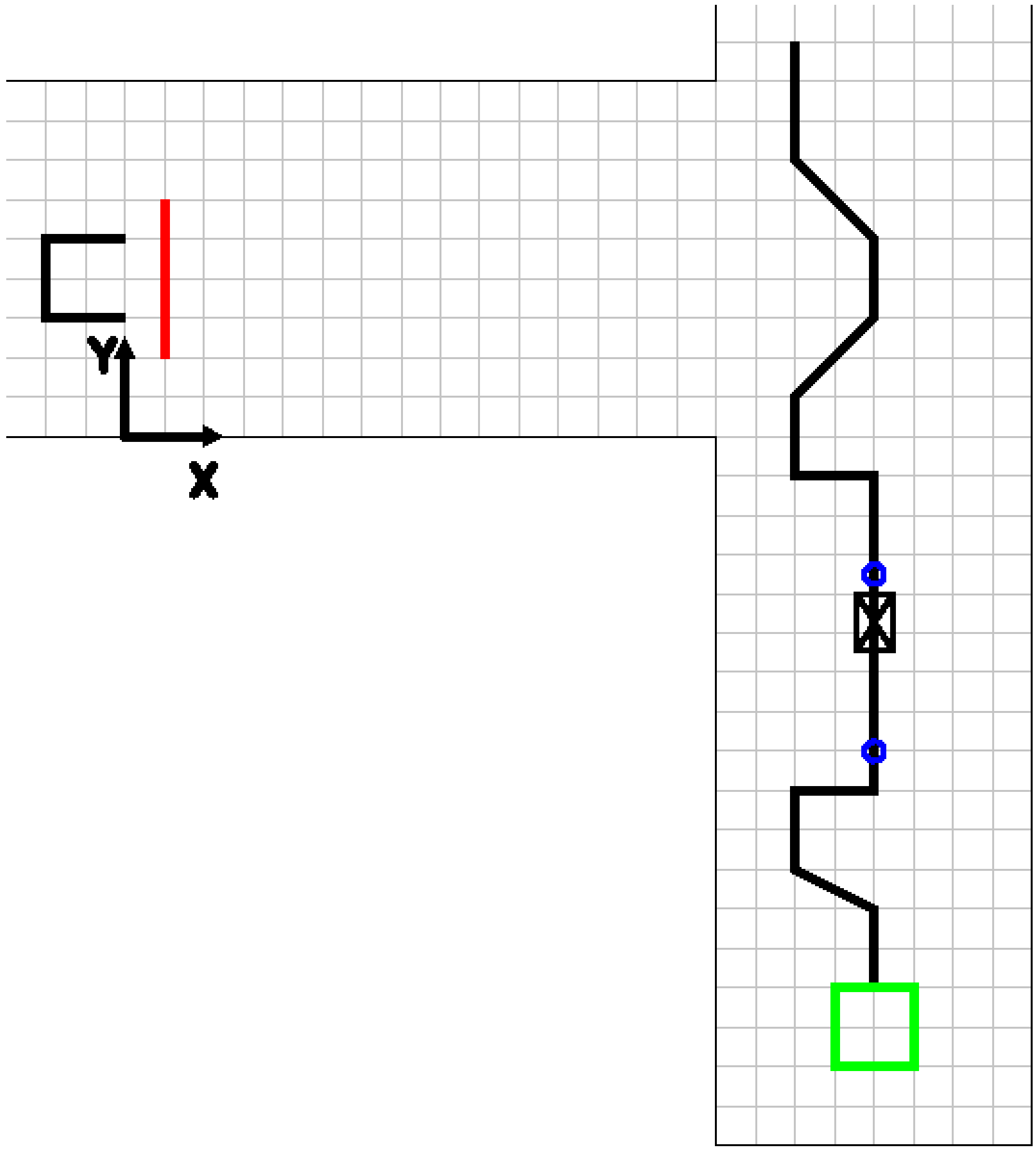
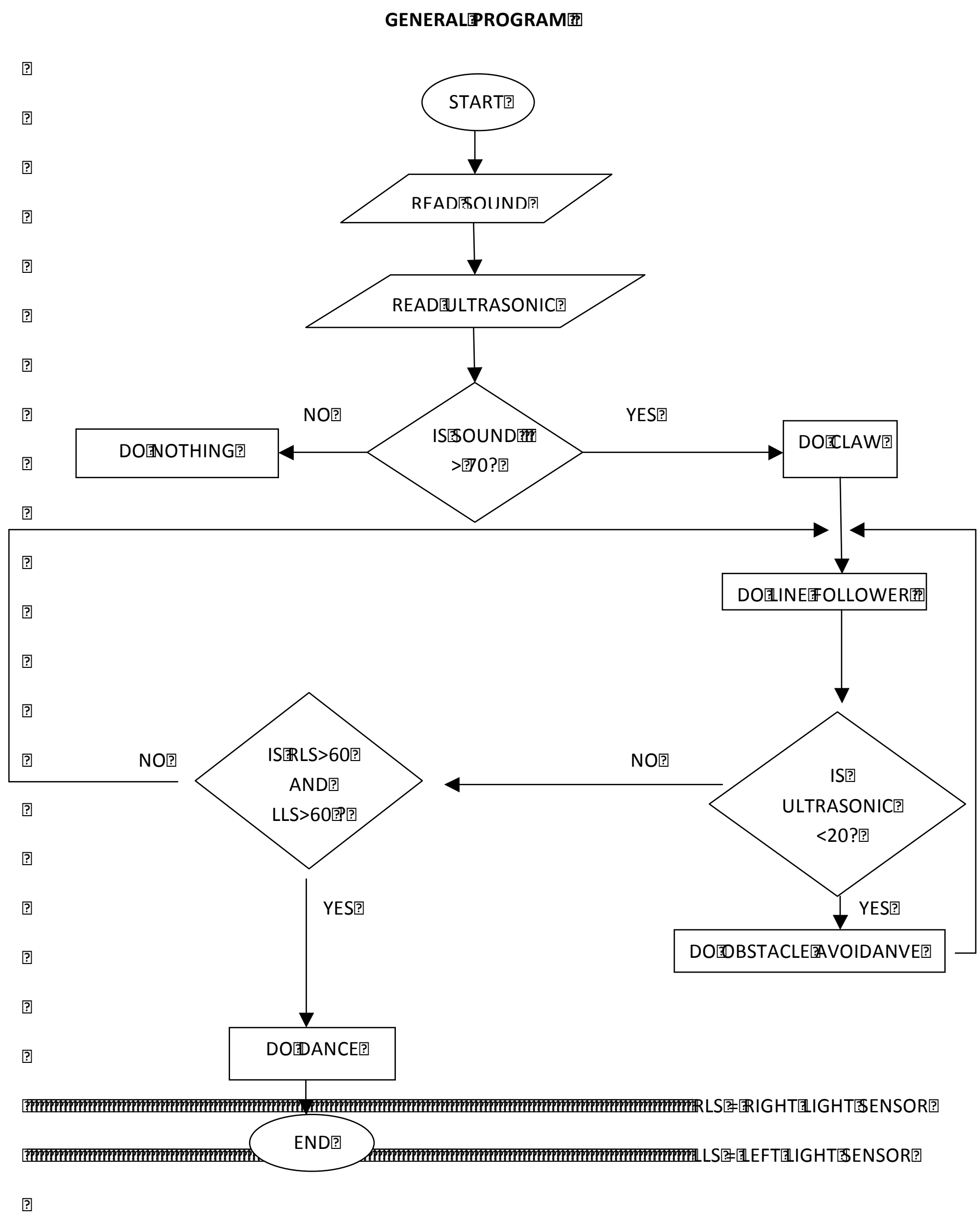
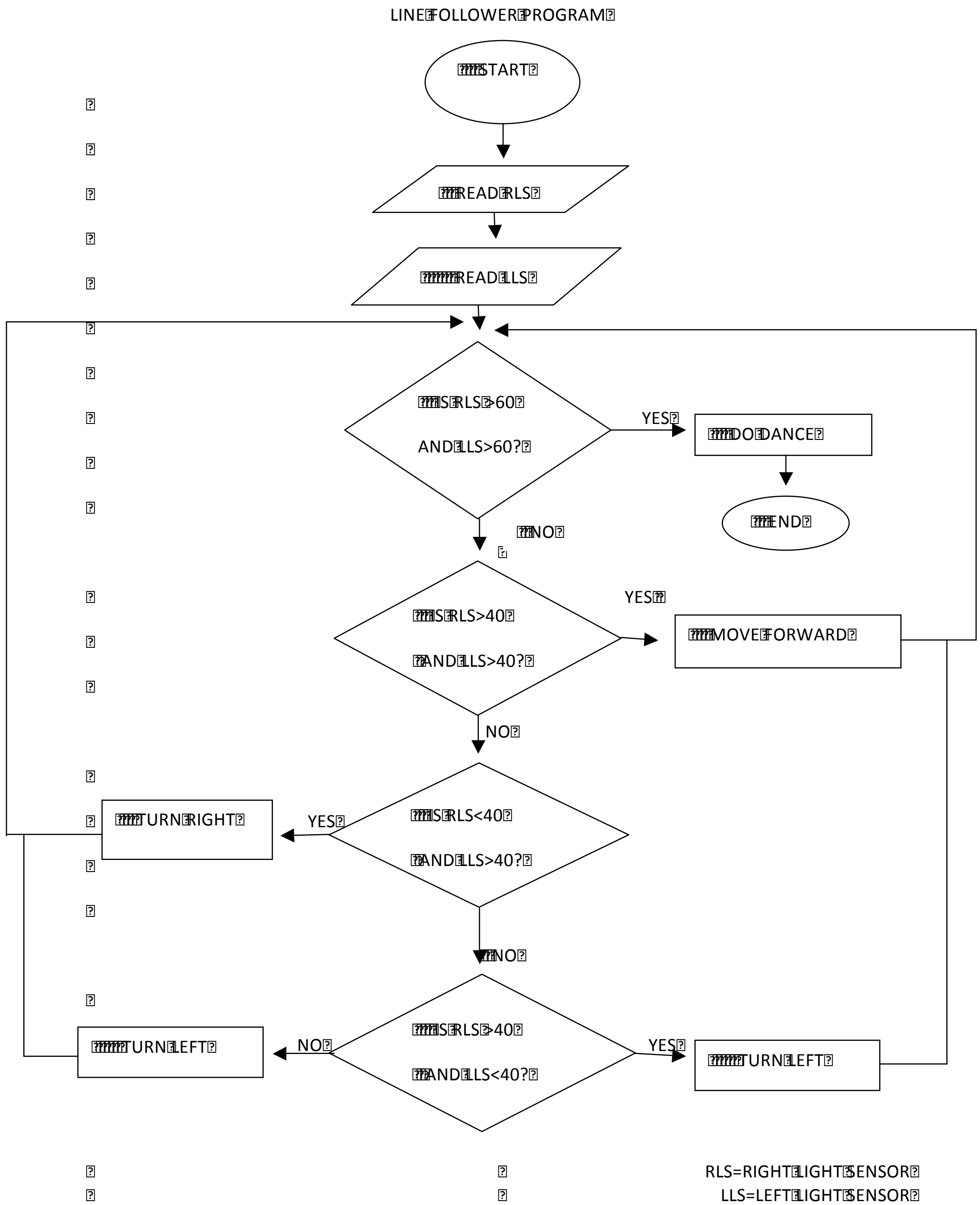
Appendix 1: UAV Path



Appendix 2: Sample UAV/robot mission flowchart

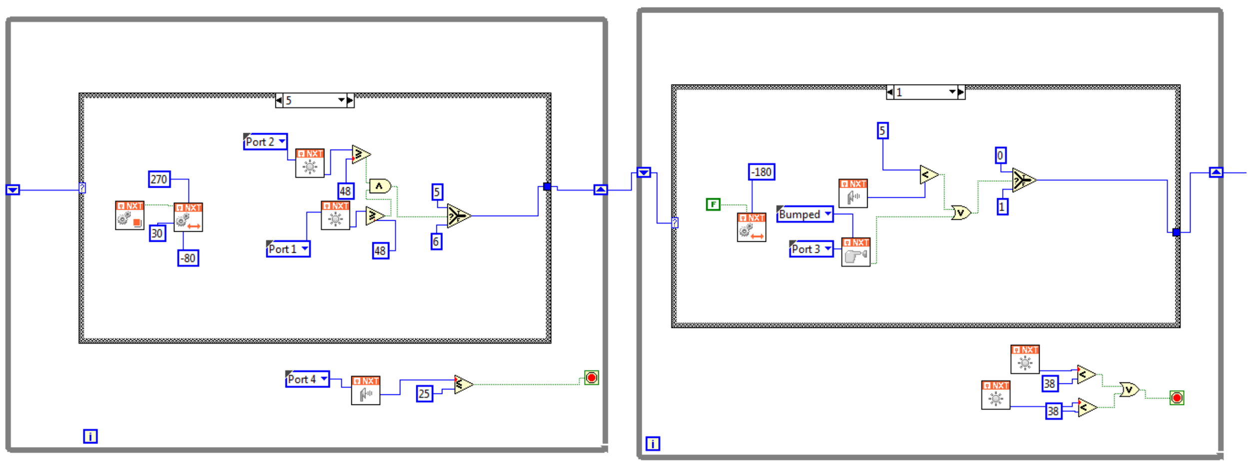


Appendix 3: Sample line follower flowchart



Appendix 4: Sample LabView code

Code 1. Following a line/ avoiding obstacle



Code 2. Only identifying line/ claw mechanism