Team CapaciTracker (Team #2):

Capaciflector-Based Tracking of a Wire for Lunar Exploration (NASA Goddard Space Flight Center)

FINAL REPORT

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Executive Summary

In order to achieve the goals mandated within NASA's Vision for Space Exploration, new and innovative approaches to space exploration must be developed. An extended human and robotic lunar presence will require large-scale production and deployment of robotic exploratory systems. Current designs utilizing rovers complete with complex collision avoidance, navigation, and research capabilities are prohibitively expensive for such a deployment. In order to reduce the cost of exploratory missions, one approach is to utilize several inexpensive application specific drones coupled with a single more complex supervisory unit. The supervisory robot could determine optimum paths for the drones to follow, deploying a wire along the length of the path as a marker. The goal of this project was to develop a simple, inexpensive, and robust system capable of accurately detecting and tracking such a wire. Other subordinate goals included designing an accurate motor control system for NASA's technology demonstrator and improving overall system reliability.

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1.0 Design Objectives/ Product Description

As a continuing proof of concept, the Goddard Space Flight Center wished to expand on the mobile robot platform previously developed in conjunction with Michigan State University. This expansion focused on further exploration into the use of capaciflector sensors. The goal of this project was to determine a way to use capaciflectors as a means of providing navigational data for inexpensive, sensor-poor robots.

To meet the goal of this project, a system capable of autonomously locating and following a wire in a lunar environment using sensor data acquired from capaciflector sensors and if necessary data acquired from additional supplemental sensors was to be developed. As NASA wished to test the developed system in Antarctica as a means of simulating a lunar environment, the design was to take this cold, hostile environment into account. However, in any case, NASA's main goal was to prove the concept worked, so more emphasis was placed on developing a functional system. Additionally, since the robot will be operating under such harsh conditions in an isolated location, NASA specified the requirement that each element of the design be made extremely robust and that they exhibit a high level of reliability.

NASA also required that the new autonomous system be integrated into the existing mobile robot platform which included, but was not be limited to, integration with the robot's Linux-based Single Board Computer (SBC), motor feedback controllers, and power supply management system. This integration additionally required that the size of the overall system not exceed the current spatial constraints. The new module had to be made space efficient, such that other modules and peripheral devices could be added in the future.

1.1 Capaciflector Sensor Array

The main objective of this project was the development of a capaciflector sensor array that could be used to track a wire or other metallic object. In terms of design requirements, there were no definite criteria that had to be met. In other words, the main goal was to simply research the possibility of tracking a wire via capaciflectors. NASA did however want the capaciflectors to be in some type of array structure and wanted research done that looked into issues involving interference.

1.2 Autonomous Wire Tracking System

The main objective of the autonomous wire tracking system was to set up the algorithms necessary to allow the robot to track a wire using the capaciflector sensors. No description as to what algorithms were to be provided was given by NASA. Rather, it was left to the team to choose what algorithms would be needed to allow autonomous tracking. NASA did however give a lot of input pertaining to the type of object that the robot should follow. In particular, NASA defined the object as being in the best case a wire, but knowing the limitations of small sized capaciflector sensors, suggested that the object be some sort of metallic strip or tape.

1.3 Feedback Motor Controller

The previously designed and developed motor controller for the robot was constructed on a wire-rap board and provided a poor level of precision movement. As a result, NASA set forth some very strict requirements pertaining to how the motor controller should be constructed and what level of precision it should achieve. More specifically, NASA wanted a motor feedback controller that was very robust, upgradeable, removable, replaceable, and accurate.

1.4 Communication Relay Board

The communication relay board was not an item specifically defined in the project description, but it was developed as a means of allowing future upgrades to the system. The issues of upgradeability and compatibility were clearly defined by NASA as factors that were to be taken into consideration during design. The communications relay board in fact was designed to meet these goals as it provides I2C communication lines for the addition of additional modules as well as legacy ports for existing circuitry.

1.5 Data Acquisition Board

In order to acquire data from the capaciflector sensors, it was necessary to develop a PIC based data acquisition module that could sample the output from a set of sensors and convert that into usable frequency data. Much like the rest of our project, this module was not specifically defined as being a component that had to be included, but it was created as a separate module to fit in with the concept of modularity that NASA wanted incorporated into the design.

1.6 On-Board Diagnostics Display Board

The concept of an on-board diagnostics display was never discussed with NASA, but it was included in the final design. The reason that this was done was so that the robot would be more user accessible and easier to troubleshoot, two concepts that were important to NASA. Also, the diagnostics module like all of the other modules made for this project was designed to be compatible with a wide variety of systems as the LCD and Keypad have been made to share one port that could be physically connected via ribbon cable to any port on any PIC microcontroller.

2.0 Design Specification

2.1 Design Criteria

Durability - The system should be designed around strict vibration and shock requirements as severe damage may be caused by a rough landing of the device on a lunar surface. The system should also be protected from damage which could result from minor collisions.

Compatibility - The system developed to allow autonomous tracking of a wire should be compatible with the systems already included in the existing robotic platform. Additionally, the system should be generic enough that it could be incorporated into other rovers and systems without the need for significant modification.

Reproducibility - The developed system should be developed and documented such that the resulting prototype can be easily reproduced.

Accuracy - The autonomous system should be sophisticated enough to stay on course without significant error.

Weight - The system must be as light as possible while keeping its strength requirements.

Reliability - The system should be able to provide reliable data even after extended periods of use. The system should also maintain reliable operation without the need for maintenance in the field.

Redundancy - Redundant systems should be included to ensure that damaged components can be circumvented without the need for manual repair. In the event a non-critical system is damaged, the system should be able to compensate for this loss.

Temperature range - The system must be able to tolerate temperature ranges from -100 to 100 degrees Celsius

Interference Rejection - The system must be shielded from external interference and immune to stray interference from other components on the rover.

Power Consumption - The system should only consume an amount of power that can be easily replenished by the power system on the robotic platform.

Size - The overall system should be small enough that it does not consume an unreasonable amount of the robotic platform's internal volume.

2.2 Ranking of Design Criteria

Rankings in decreasing order of desirability. (Five is most desirable. One is least desirable.)

Design Criteria	Ranking
Interference Rejection*	5
Compatibility*	5
Accuracy*	5
Reliability*	5
Durability	4
Power Consumption	3
Reproducibility	2
Redundancy	1
Size	1
Temperature Range	1
Weight	1

Table 1: Ranking of Design Criteria

*: Categories that must be satisfied for a design to be feasible

2.3 Specification Overview

Throughout the course of this project, the design criteria have played a major role in the development of the final product. However, it is not the case that all were given equal weight.

Rather focus was simply placed on only a few of the criteria. The criterion of most importance was interference rejection. The reason this is the case is that interference can cause the output from the capaciflectors to be unusable, in terms of the fact that they cannot produce stable and reliable output waveforms. The second key design criterion was compatibility. This was a major issue in this project as the robotic base serves as a continuing "proof of concept" platform. More specifically, in future semesters it is likely that a whole new group of students will be working on adding new components to the system or enhancing and expanding upon existing systems. In addition to interference rejection and compatibility, accuracy and reliability criteria greatly influenced how the system was designed. In terms of accuracy, many hours of work were put into verifying that the motor controller circuitry functioned with a high level of normal operating precision. Additionally, tests were repeatedly performed on the capaciflector sensors to assure that detection of a wire occurred when appropriate and that there were no spurious glitches in either the reference condition or in conditions where metal was present. Issues of durability, reproducibility and redundancy also helped to define project design. To ensure durability, a Plexiglas shield enclosure was constructed that protects the capaciflector sensor array from damage that could result from impacts with foreign objects. To guarantee reproducibility, the actual circuits for the capaciflector array and motor feedback controller circuit board were laid out within printed circuit development software. In terms of redundancy, additional sensors were added to supplement the existing capaciflectors. The remaining design criteria were less relevant in the scope of this project as the sponsor made it clear that proving that the sensors could be used outweighed issues such as power consumption and temperature range. Therefore, although these issues were quite often considered, they were trumped by issues such as availability and needs constraints.

3.0 Final Design Implementation

3.1 Capaciflector Driver Circuitry

There are many applications for capaciflectors, but most applications fall into two main categories, proximity and material detection. Both of these categories require a unique capaciflector driver circuit to make them function. For the proximity applications a constant frequency was applied to the sensor and shield plates and a change in this frequency caused by a capacitance built up between the sensor and object was monitored in order to determine the object is present. The material detection applications require a little more circuitry. It requires a frequency scanning circuit that compares the readings of an object, which is dependent on its permittivity, with a database of known values. A microcontroller can store this database and match the current reading of the capaciflector and oscillating frequency with one in the table and identify what type of material is present. Figure 3.1.1 shows our application that involves a motorized robot that would follow a conductive material such as wire lying in a path on the ground. Figure 3.1.2 shows the array of capaciflector sensors we made and attached to the bottom of the robot.

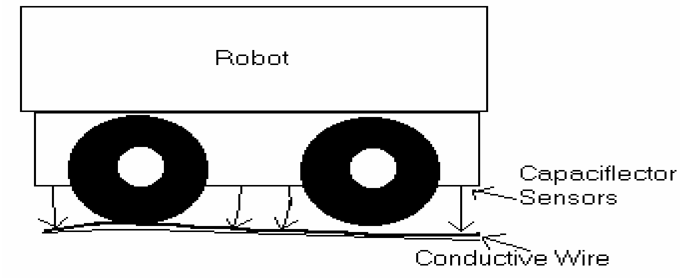


Figure 3.1.1: Robot Side View

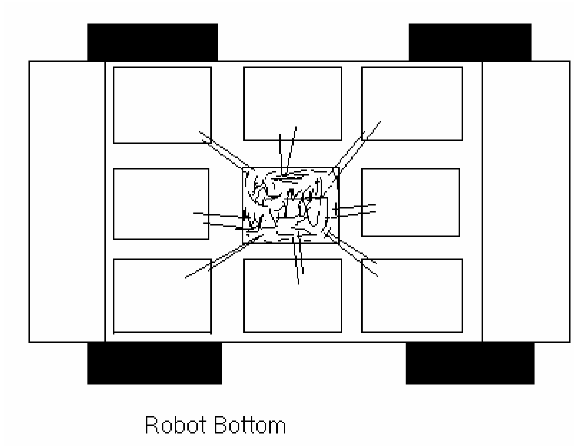


Figure 3.1.2: Robot Bottom View

Control Circuits Tried and Tested

The circuits in Figures 3.1.3, 3.1.5, & 3.1.6 were reviewed based on functionality as well as dependability. The Cheung circuit design shown in Figure 3.1.3, has a 1M ohm trim pot used for R11. This pot was used to adjust the frequency of oscillation of the sensor's plates for optimal performance. Using the oscilloscope to read the oscillating signal, testing was done to determine what frequency would cause the sensor to work optimally. It was found that when the potentiometer was set such that the oscillation frequency was set to 250 kHz the sensor was most sensitive.

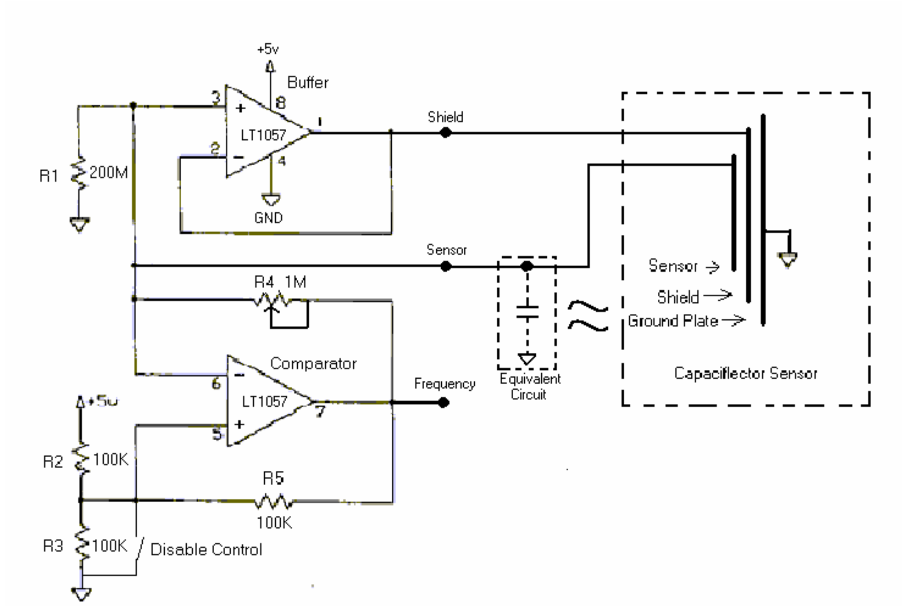


Figure 3.1.3: © Dr. Edward Cheung's Capaciflector Driver design.

The graph in Figure 3.1.4 shows that the output frequency increases exponentially as the sensed object gets closer to the capaciflector sensor. (Barnhart)

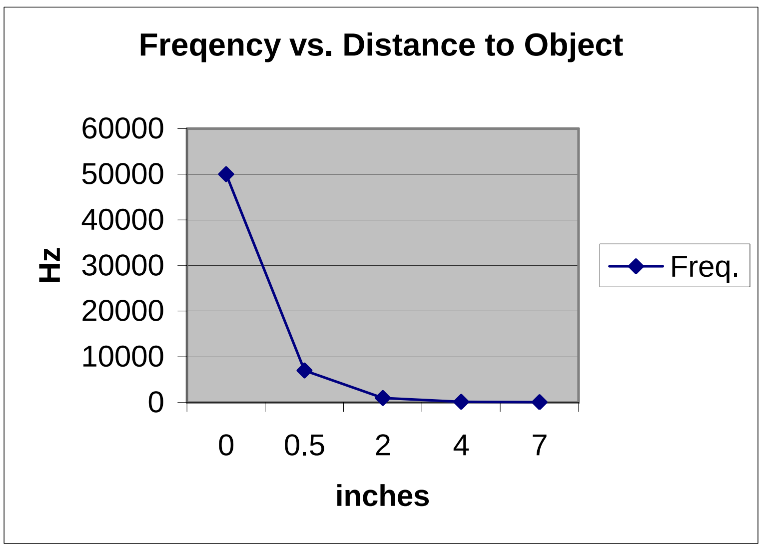


Figure 3.1.4: Chung's Circuit Frequency Response

The Stanford driver is shown in Figure 3.1.5, and is fairly straight forward and easy to build. The Stanford driver was considered briefly, but it was decided that it would not be the best choice because it did not have the exponential sensitivity found in the Chung design described above. So this design was not considered further.

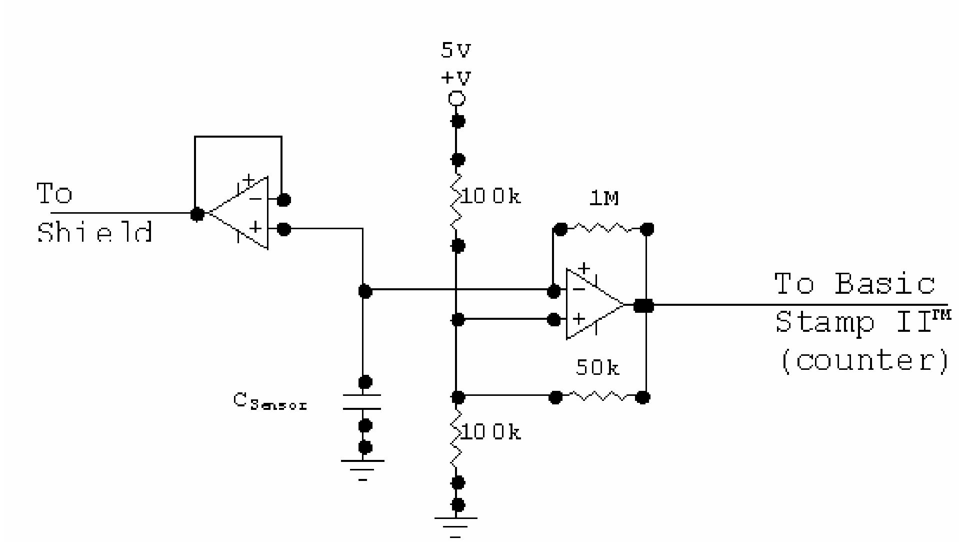


Figure 3.1.5: Stanford's Capaciflector Driver design. (Smaby-1)

The circuit below in Figure 3.1.6 is a little more complex than the two above, but it can determine not only the proximity of an object but also the type of material being detected. This circuit was built and tested using LT1057 op-amps and a function generator to provide a frequency sweep. The results of the testing were that the output voltage Vo did in fact change when an object approached the sensor plate. However, this change was in the magnitude of a few millivolts and was not significant enough to reliably distinguish it from noise. This circuit was tested using a four-inch capaciflector. Since this circuit works on the principal of a potential difference between the sensor plates, it was hypothesized that a significantly larger plate would work with this system. However, due to the size limitations on the bottom of the robot as well as the sensor array that we wanted to implement, large sensor plates would not work. So this method of detection had to be abandoned.

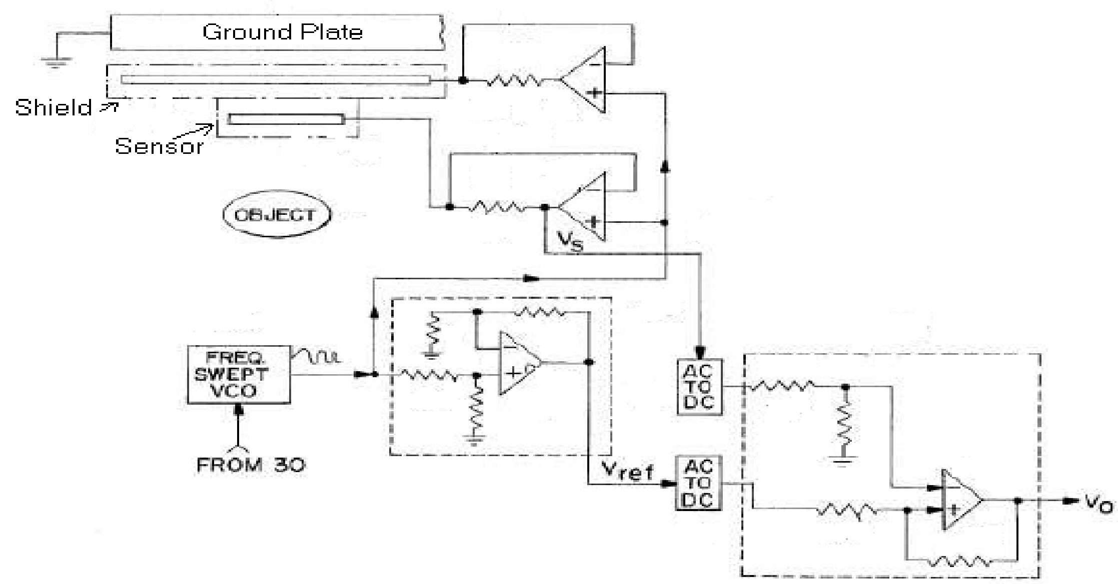
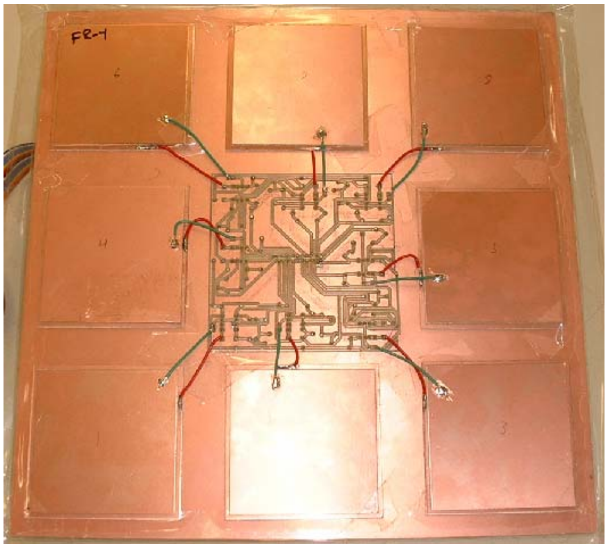


Figure 3.1.6: © NASA's Frequency Scanning Driver Design. (NASA)

Based on the testing described above, the team decided to implement the Chung proximity detection capaciflector driver circuit. Further testing was done on the eight capaciflector sensor array using the Chung designed control circuits constructed in the middle as seen in Figure 3.1.7. The results of the testing can be seen in Table 1 in Appendix C. The circuit was constructed in the middle of the array in order to minimize noise due to the close proximity of the circuit to the sensors. This also eliminated the need to use shielded Triax cable, which was bulky, costly, and hard to work with.



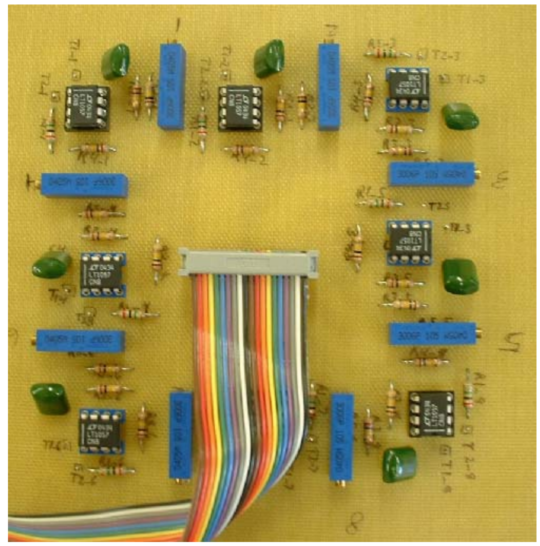


Figure 3.1.7: Capaciflector Array and Driver Circuitry

Issues

Some distortion of the output signals of adjacent sensors was noticed, when using the array of eight sensors oscillating at the same time. A disable signal was added by the method shown in Figure 3.1.3, and the sensors were enabled one at a time to retrieve each sensor's data and cycle through the whole array one at a time. This eliminated the interference from sensor to sensor.

Problems and Solutions

It was found that when the frequency of oscillation of the capaciflector driver circuit was set to the optimal frequency of 250 kHz that the output voltage was around one and a half volts peak-to-peak. This was not a high enough voltage level for the microcontroller to see the signal as an input. So the frequency of oscillation had to be set lower so the voltage would be at a readable level. It was determined through testing various frequencies, that 100 kHz would give an output voltage of 3.5 to 4 volt peak-to-peak. This voltage was sufficient for the microcontroller to register the signal as an input. The test results found at 100 kHz can be seen in Table 3.1.1.

Table 3.1.1: Capaciflector Test Results @ 100kHz

Sensor	Voutput	Frequency Swing kHz
#3	3.5v	100-95
#6	3.7v	100-88

#5	3.0v	100-82
#4	3.56v	100-83
#2	3.41v	102-95
#1	3.56v	101-85
#7	3.59v	99-87
#8	3.46v	99-83

3.2 Capaciflector Sensor Array Design

Overview of Capaciflector Design

A capaciflector sensor system was used in this project. The specifications of the overall system can be seen in Table 3.2.1. The capaciflector was made out of a printed circuit board material, or substrate board. This was chosen for its high reliably and robustness over weaker foil sensors. The substrate board itself is a material composed of one layer of copper mounted onto an insulator. One layer substrate board was chosen over two layer substrate board, as it provided a means on separating the layers of the capaciflector by larger distances. Additionally, using the one layer board prevented the need to use a computer numerically controlled (CNC) machine to mill the top side of the plate to create the sense plate.

In terms of the substrate board dielectrics, a board with high dielectric properties was chosen as it was shown to provide the highest level of sensitivity. More specifically, a one sided copper RF-4 board was used. This board was also chosen on the basis of dielectric thickness as the RF-4 board provided a relatively thick dielectric. Testing proved that a thicker substrate provides greater range and performance. The RF-4 boards were cut to the appropriate size constraints by a shearing machine such that they all had similar dimensions that would result in similar properties.

In addition to the capaciflectors, additional supplemental sensors were added to compensate for some of the capaciflectors that simply did not exhibit good range or that proved to be for the most part non-functional. These sensors were optical based sensors and worked through the use of phototransistors and high intensity light emitting diodes. These sensors were added in conjunction with the capaciflector system to allow for a more accurate representation of the objects being sensed. The sensors also provided a good redundant system that could be used to validate the capaciflectors and the autonomous control algorithms. The circuitry for the light based sensors was that of the existing capaciflector control circuits. Simply, the capaciflectors that did not work were severed from the array and via simple modifications to the capaciflector controllers, the photo transistors were integrated to function in there place.

Table 3.2.1: Capaciflector Specifications
Ground Plane: 30.5 x 30.5 cm
Shield Plate: 8 x 8 cm
Sensor Plate: 7.5 x 7.5 cm
Driver Circuit dimensions: 10 x 10 cm
Plate Material: 0.2 cm thickness RF-4 substrate board

Grid Design- With On Board Driver Circuit

The capaciflector multiplexer system was created using an unprecedented design. This includes a grid of multiple capaciflectors with onboard driver circuits. A large common ground plane substrate board was used as the base, so the sensor array would be rigid and there would be a region where the circuit traces could be CNC milled into the array board. The total number of sensors include on this board was eight. These were positioned on the border of the array such that when mounted on the underside of the robot, they would cover the perimeter of the robot's base. The center of the grid, the green region in Figure 3.2.1, contains the control circuitry for the capaciflector sensors. Placing the control circuitry here removes the need for external wiring to the capaciflectors, therefore reducing noise.

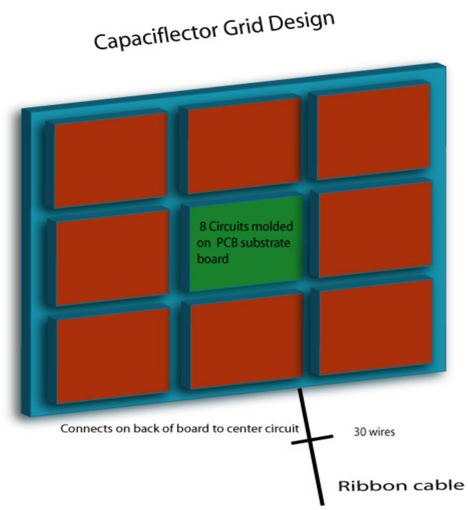


Figure 3.2.1: Capaciflector Conceptual Array Design

Using a cable to transfer the outputs from the capaciflectors to the external control board was also tested thoroughly. However the logistical issues of using a cable along with interference issues ruled out using this option. Also, the mere bulk of the shielded cabling itself made it impossible to attach the wire to the plates in the capaciflector structure.

Two optical sensors were placed on opposite sides of the capaciflector grid to allow for an additional sensing device. These sensors allowed for an even greater range of sensitivity over the capaciflectors. These sensors required no additional calibrations to the existing hardware or software as they work on the same basic principle as capaciflectors sensors, meaning that they also elicit changes in frequency.

Sensor Output

The system was designed to allow for data to be transferred from the capaciflector board to the PIC microprocessor board. These outputs were connected with a ribbon cable. This cable was made relatively short such that large amounts of capacitance would not be added to the system. The ribbon cable also provided a means of transferring the enable/disable signal to the capaciflector control circuitry uses the remaining wires in the ribbon. These control lines are required as only one capaciflector may be used at a time to eliminate interference between the sensors.

Testing

The capaciflector grid was calibrated for consistency. The driver board’s variable resistors were adjusted individually to allow for maximum calibration. This calibration was also performed in the software aspects of the algorithms. The testing showed that the capaciflectors were very susceptible to range fluctuations. The results were averaged in software to create a useable output. Only 4 of the capaciflectors were used for the tracking due to interference issues of the sensors. The capaciflectors were tested with several types of materials under it, and while moving. The interference problems due to the motors were resolved by adding an additional optical sensor for additional data input. Overall the sensors were effective for the tracking project; however they can be only used under controlled conditions.

3.3 Capaciflector Mounting

There were numerous ways considered as to how to attach the capaciflector grid to the rover. There were also many variables to take into account when looking into the future use of the machine. Environmental factors played a large role in the manufacturing of the finalized mounting device. When the rover is to be tested in Antarctica the robot will be exposed to powerful winds and possibly moisture from snow or ice. Taking into account these two factors the rover would need to be completely encased by a rigid projective barrier as water droplets could surely cause damage to the built-in circuitry and high winds could affect the capaciflector readings from height variations caused by physical shaking.

Although protection from the environment is important, it is convenient to have visual access to the sensor grid without having to remove any hardware. Also to account for future improvements to the system, for example in instances where different capaciflectors with different dimensions are added to the system, the enclosure must be able to adapt to sensor additions or modifications. As the science in this field improves the range of the sensors will undoubtedly increase so the distance from the target object to the sensors can not be fixed. It is therefore a necessity to have a mounting system that allows lowering and raising of the mounted array platform.

The design is mounted to the underside of the robot as shown in Figure 3.3.1. The longest standard bolt size available in the 6-32 size is two inches long. This size was not long enough to yield the results needed by the project as two and three quarter inch bolts produced the most favorable output from the capaciflector grid. Tie rods were purchased and cut down to the appropriate size and nuts were used to cap off the bare threaded rods to create homemade bolts. Using the tie rods allowed for a dynamic ground clearance. As shown in Figure 3.3.1, black rubber washers were placed to protect the Plexiglas as well the circuitry itself. Locations for the ‘bolts’ were chosen mainly by the space allowed from the components located inside the rover. For example the batteries covered much of the surface area available for ‘bolt’ holes so having evenly spaced mounting positions was not possible. The final rover ground clearance after the addition of the mounting package was only about half an inch, but this is a result of range limitations as opposed to a flaw in mounting design.

Figure 3.3.1: Protected Capaciflector Grid Attached to Rover

The final design implemented also includes a Plexiglas housing protected by weatherproof stripping. In order to protect both the trace routings and the capaciflector circuitry components a flat plane of Plexiglas was used to protect the routing side and a half inch Plexiglas compartment was constructed to protect the components as shown in Figures 3.3.2 and 3.3.3. The Plexiglas was constructed in a manner to sandwich the weather stripping. Frost King X-treme Rubber Weather seal was used in this instance.

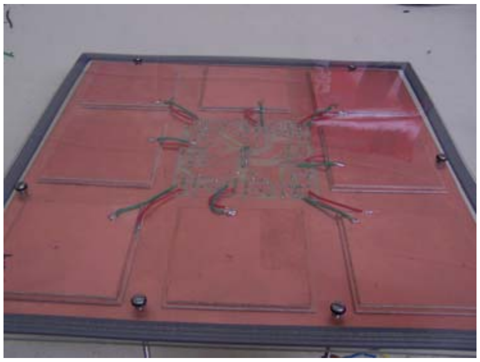


Figure 3.3.2: Bottom of Mounting System

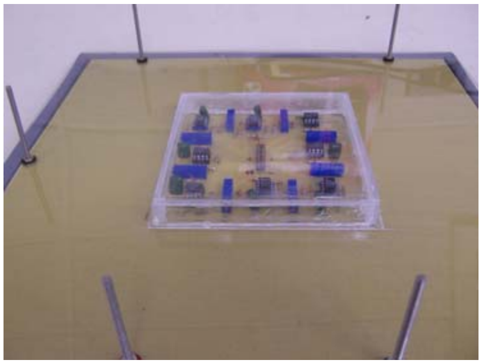


Figure 3.3.3: Compartment on Mounting System

Note: Figures 3.3.1 to 3.3.3 are shown with prototype bolts, not pictured is the designed tie rod ‘bolt’ system.

3.4 Autonomous Wire Tracking System

The system used to quantify the data from the capaciflector sensors for use in the intelligent tracking routines was based on a simple yes/no condition. A “yes” meaning that a wire lay within range of the capaciflector sensor and a “no” meaning the opposite. In order to generate this simple yes/no condition for each sensor in the array, the following procedure was implemented. First, frequency data values were passed in integer form from the data acquisition PIC microcontroller to the SBC via a RS-232 serial communications port. These values were then compared against a base set of calibration readings, which were obtained via an automatic calibration routine. The basic concept chosen for this routine was one that determined the range of fluctuation exhibited by the capaciflectors in the reference state. More specifically, the algorithm was designed to determine the maximum and minimum values that the capaciflectors reached in the reference state. This determination was accomplished via continuous polling of the capaciflector sensor array for more than two hundred times. A period of roughly two hundred was chosen as it was found through experimental testing to sufficiently predict maximum and minimum values. Although the predictions were for the most part accurate, the simple definition of maximum and minimums did not resolve all glitches in either the reference or metal detection states. With this being the case, it was necessary to include manual calibration settings for each sensor in the array. Although this may seem to defeat the purpose of automatic calibration, this manual type of calibration serves as a means of compensating for variances in capaciflector readings as the result of non-uniform construction. Once the sensors themselves have been manually adjusted, the automatic calibration can compensate for issues specifically relating to changes in the operating surface. To test this concept, after manual calibration was completed on all the sensors, the automatic calibration routine was tested on a number of different surfaces including carpet, cardboard, tile flooring, and wood. In all cases, the manual calibration succeeded in creating a state where no glitches occurred in either the reference or metal detection conditions.

Although the routine for automatic calibration worked for most sensors, there were some sensors that simply could not be calibrated. The reason that this was the case is that some of the sensor's output frequencies did not produce a change in frequency that was greater in magnitude than normal fluctuations. It was therefore necessary to reject data from these sensors via software. In some cases, these sensors had to be replaced with supplemental light based sensors. This solution was chosen in situations where the faulty capaciflectors were positioned in key portions of the array needed for intelligent decision making.

The comparison of current sensor readings to the base state fluctuations of the capaciflectors involved the use of a running average. Each time a new piece of data was read into the system, it would be averaged into an existing set of averages. By doing the averaging in this way, delays associated with averaging completely new sets of data could be avoided allowing for more fluidic robot movements. Checking this average against the range of fluctuation allowed for a simple conversion of the integer form data into binary form as the value would be zero within the range of fluctuation and one outside of the range. The storage of the previous set of binary data allowed easy determinations as to whether or not transitions from zero to one or vice versa occurred on the array.

In terms of the software for data quantification, several other options were considered. The first was the development of distance readings using the frequency readings from the capaciflectors. This method was rejected as computing the distance value given by a capaciflectors would have been overly complex and would have provided little additional information as the capaciflectors had to be mounted very low to the surface of the ground. Additionally, the routine used for automatic calibration evolved over the course of time. The actual calibration routine for the capaciflectors was originally designed based on percent change from the mean. However, when this was executed in software, it proved to cause errors as the result of rounding and truncating effects associated with multiplication of the integer form sensor data with the floats representing tolerance. By instead comparing the data against a range of fluctuations, this error was eliminated as the current sensor data could be logically compared against other integer values. Different types of averaging were also considered. The averaging system first implemented would read in twenty new values each time it computed a current average. This process proved to greatly reduce the robot's response time, and as a result the faster running average was chosen as the main averaging technique. In terms of averaging and quantification of data, including this code on the PIC was also considered. This approach was rejected in favor of performing computations on the SBC. The reason that the code was not included on the PIC was that it would have introduced significant delays into the system associated with the additional time needed in each timer interrupt service routine to compute the single bit form of the data. Including the automatic calibration on the PIC would have introduced similar problems as there would have been a lot of time spent in the calculation of the calibration data. Also, the programmer would have had to reprogram the PIC every time he/she wanted to adjust manual calibration parameters. By including this on the SBC, the programmer can simply update and recompile the file.

A few different wire tracking schemes were considered for use in this project. These include a two state approach, a four state approach, and an augmented four state approach. These finite state models are defined as follows:

- Two State – This approach employs the use of only two states. The first is the Track state in which the robot's wheel velocities are regulated in order to keep the sensor values equal. This ensures the wire will be directly beneath the robot. The other state is the Help state. This state is activated when the sensor measurements drop below a specified threshold, indicating that the wire has been lost. At this point the robot stops all motion and indicates to a remote operator (RO) that it requires user intervention. The RO drives the robot back within sensor range of the wire.
- Four State [9] – Its initial state is the Search state, wherein it drives in a straight line until sensor readings indicate that a wire has been found. It then enters the Rotate state, where the robot rotates until sensor readings indicate that the robot is straddling the wire. At this point, it enters the Track state, in which wheel velocities are regulated to keep the wire centered underneath the robot. The final state is the Backup state, which is only entered from the Track state after sensor readings drop off below a given threshold for a given amount of time. This state causes the robot to back up in search of the wire. The robot will backup until the wire is reacquired or will stop after a predetermined timeout. In the case of a timeout, the robot will enter the Search state.
- Augmented Four State – This control scheme is much the same as the Four State above. However, proximity sensors are added to the robot to prevent collisions with obstacles while in the Backup and Search states. Also, the Search state is modified to search in an outward spiral pattern centered at the last known location of the wire.

The model chosen as a conceptual base for use in this project was the four state model. All of the software was developed from scratch and modifications were made to the state model such that it was made application specific to this project. The search state was almost eliminated as the robot did not stop on the wire. Rather, an assumption was made that the mother robot would deploy her drones such that the wire is in the center of the drone's paths. The robot will only transition into a rotate state when one of the sensors that are on either side of the wire is tripped. In this way, the robot will move forward until the wire is leaving the dead band between the sensors on the left and right side of the robot. When this occurs, the robot enters a rotate state. In this rotate state, the robot rotates until the wire moves back into the dead band. In addition to modifications made to the rotate and search states, the backup state was essentially removed. The reason this had to be is that the robot has no way of telling if it passes over the end of the wire as it will believe that the wire is still in its dead band.

The reason that the two state and augmented four state models were not chosen is that they represented situations that were not desirable. In the two state model, the robot is not fully autonomous. Therefore, it would require continuous user interaction. The augmented four state essentially only runs into its modified search state when the wire is lost, and as there is no way of entering the backup state, there is no need to relocate the wire using the spiraling technique.

3.5 Feedback Motor Controller

The Feedback Motor Controller is a Microchip PIC16F877 base board with inputs for four Motor Encoders. Each of the encoders transmits signals on three lines: channel A, channel B and Index. The connections for the Motor Encoders allow for these three lines and also include terminals for the logic power. In addition the Feedback Motor Controller has connections for up to four motor controllers. This includes a transmit line and power lines to each motor controller. In addition there are two power supply connections to the board itself. These two supply line can be isolated from each other so that the encoder and motor controller supply is separate from the microcontroller supply. They can also be jumpered together so that all three components can be run from the same supply line.

Final Design Implementation

The system developed for feedback based control of the mobile robot platform’s motors includes several modular components. The motors used for propulsion were items inherited from the previous semester’s project, as were the encoders affixed to each. The encoders produce three channels of feedback, with two channels providing fine resolution feedback and directional information and the third providing a reference pulse each motor revolution. The project required that these motors be able to respond accurately and predictably to commands issued through the Single Board Computer. Also inherited from the previous semester were serial motor controller modules, capable of accepting commands at TTL levels and converting those to a driving signal to the motors. In the hopes of being able to utilize tested and proven components, these were also included within the final design. The main task then became to integrate the existing motors, encoders, motor controllers, and SBC into a precise and responsive motion control system. It was decided that the use of a PIC microcontroller would provide the necessary flexibility and functionality required in such an application. The PIC 16F877 was viewed as an ideal choice, as it possesses a hardware based RS-232 communications interface, has ample interruptible input pins, and can be programmed using commonly available tools.

System I/O

After much time and effort, it was decided to utilize the index signal from each motor encoder as the primary feedback signal for distance feedback. The first design attempted used both channels A and B from each encoder to derive both distance and directional information. Utilizing the real-time clock on the PIC would also allow the computation of the current velocity. However, due to the high gear ratio of the motor (157.2:1) and the high resolution of the encoders (2048), the amount of throughput required to process the feedback data was too great for a PIC to provide. Upon utilizing the index lines from each motor controller as inputs to the interruptible pins on the PIC, it was found that the PIC was not able to accurately count the number of pulses coming from that line. After investigating the signal coming in over the wire, it was found that the index pulse width was only 10 us. This was not long enough to sample reliably with the interrupt based inputs on the PIC. Therefore, a signal conditioning module was added to the design. This consisted of four J-K flip flops set to toggle on each clock pulse. The index pulse served as the clock input. This generated a clean square wave, which served as a much more reliable input. The interface to the motor controller consisted of a simple one wire serial communications protocol run from the PIC's hardware serial communication module. As each motor controller had a unique channel number, both controllers could share the same input line. The interface to the SBC consisted of a unidirectional serial communications line from a COM port on the SBC to the hardware serial receive pin on the PIC. Bidirectional communication to provide feedback to the SBC was not investigated as several other components in the overall project design were suffering from various communications issues throughout the design period. As this system would serve as the infrastructure for all teams utilizing the robot, reliability was viewed as one of the main goals. Therefore a system relying on unreliable communications was not seen as desirable. The SBC's COM ports operate at standard (12V) serial levels and therefore needed to be converted to TTL (5V) levels. This was accomplished through the use of a serial converter board, including the MAX232 converter chip.

PIC Firmware Design

The PIC firmware was designed around an interrupt based system to allow for optimum throughput. It accepted integer values specifying the desired distance and velocity for each side in terms of the number of index pulses detected. It was fully commented to allow for ease of future development. It currently keeps an accurate count of the index for use in determining when to actually stop the motors for use in precision movements. It then converted these to the appropriate commands for the motor controllers. It then appended the address of the destination controller and sent the commands via the RS-232 TTL level interface.

SBC Software Design

The software on the SBC was designed simply to take values from a telnet session as floating point numbers, in terms of desired distance, turn angle, and velocity. It would then convert these values to be specified in terms of the number of counts required for the motor encoders. It would also compute the necessary commands to enable precision zero point turns.

3.6 Communication Relay Board

The Communication Relay Board was design to eliminate the need to use numerous serial ports for every expansion module. In theory the board is able to connect to the SBC using the standard RS-232 communication protocol and transmit that data to the expansion modules using the standard I2C communication protocol. The Communication Relay Board has two channels for I2C and on each channel there are four connectors that will be used to connect the I2C clock and data lines to the expansion modules. Since only one expansion module will be able to transmit at a time more than one module can be connected to on each line. The two separate channels were implemented to alleviate any excess communications on the line because every module will need to listen to the data being sent and decide if that information was intended for it.

3.7 Data Acquisition Board

The Capaciflector Array Data acquisition Board, seen in Figure 3.7.1, is designed to enable and disable each capaciflector to allow for counting the signals produced by the capaciflector array. This board contain a Microchip PIC16F877 running at 20MHz and a header that connects directly to the Capaciflector Array. Port D on the Microchip PIC is connected to the signal output of the capaciflector array and Port A and E are connected to the enable pins of the array. The software samples each capaciflector for a given amount of time and counts the changes on that signal. In addition every port of the microcontroller is available at custom headers with pull-up or pull-down resistors for future expansion.

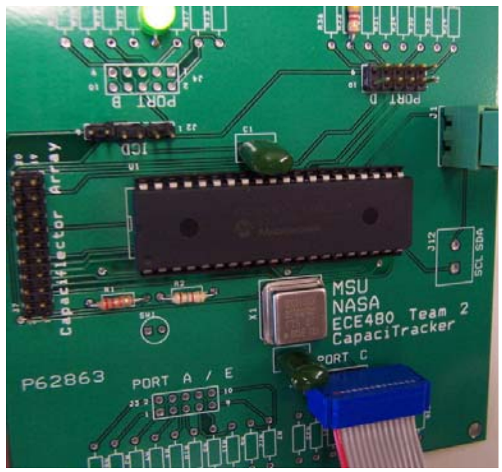


Figure 3.7.1: Data Acquisition Board

3.8 On-Board Diagnostics Display Board

The data acquisition board was created as a portable peripheral device that could interface with any of the PIC microcontroller boards designed for this project. The main source of debug information is passed via RS232 to the SBC for display on the screen, but there could be situations were a user would like to perform diagnostics right on board the robot. For example, if the SBC were out for repair or if the error was at a point in the system that caused a block of RS232 passed messages. In a case like this, each board could be diagnosed individually. A picture of the diagnostics display can be found in Figure 3.8.1.

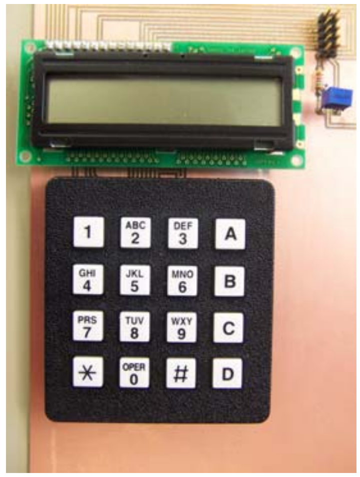


Figure 3.8.1: Diagnostics Display Module

4.0 Final Design Performance

The motor controller system was completely successful. The entire system interfaced successfully with the other subsystems. The system computed displacement in real time. It was also capable of executing turns with minimum of 5% accuracy before accounting for wheel slip. In addition the motor controls are accurate to within 2cm prior to considering vehicle dynamics. The motor control system was also successfully tested with heavy load and reverse motor feedback. The system was protected by the reverse EMF motor protection circuit.

The capaciflector system worked successfully at a stable distance. The sensors are extremely sensitive to variations in distances. Calibration and averaging corrected small fluctuations with the system. The system successfully detected the location of a metal object and made intelligent decisions in the software based on this. The capaciflector, software, and motor control system all made decisions in real time, while communicating to each of the systems.

5.0 Summary of Design Team Organization and Roles

The team was organized into three discrete groups. These groups coordinated together to produce the final product. Each member also had a non-technical role established.

Group 1: Remote Management System, Tracking Algorithms, and Sensor Data Acquisition

Gary Crum (Liaison)
David Skalny (Documentation Coordinator)

Group 2: Motor Controllers Hardware and Software/Tracking Algorithms

Craig Pomeroy (Presentation Coordinator)

Group 3: Capaciflector Design, Fabrication, and Testing

Austin Matero (Project Manager)
Sean Coleman (Lab Coordinator)
Derek Sokoloski (Webmaster)

Detailed Breakdown of Non-technical Roles

Member	Role	Duties
Professor Aslam	Team Facilitator	• Overlook the team's progress on a weekly basis • Review documentation prepared by the team
Austin Matero	Project Manager	• Maintenance of team schedule and Gantt chart • Management of project Budget
Derek Sokloski	Webmaster	• Setup and maintenance of the team's website.
David Skalny	Document Preparation	• Organization and compilation of all reports and documents for the team
Craig Pomeroy	Presentation Preparation	• Development of professional oral and visual presentations
Sean Coleman	Lab Coordinator	• Acquiring of all parts and equipment needed for the project
Gary Crum	Team Liaison	• Establishment and maintenance of communication between the various NASA teams

Detailed Breakdown of Technical Roles

Capaciflector Sensor Hardware	
Austin Matero	<u>Capaciflector Materials/ Specialized Cabling</u> Mr. Matero, using experience in communications and electronics, will create a capaciflector prototype, which has the ability to create accurate and consistent results. This will require performing tests using different metals and dialectics to construct the capaciflectors. Mr. Matero will also work on determining which type of cabling is best for retrieving viable data from the capaciflector sensors.
Sean Coleman	<u>Controller Electronics</u> Mr. Coleman will develop a prototype and working PCB for the capaciflector controllers. These controllers will be developed in such a way that the proper sensitivity needed to detect a strand of wire exists. Mr. Coleman will also make considerations into developing circuits that have built-in redundancies so that bypassing damaged circuits is possible. Mr. Coleman will also ensure the controllers maintain compatibility with the PIC microcontroller.
Derek Sokloski	<u>Test Coordination</u> Mr. Sokloski will lead the testing of the capaciflector controller hardware and circuits to verify that the controller can successfully locate and lock onto a wire. Additionally, Mr. Sokloski will determine the array density and size that provide the most accurate and reliable data.
Capaciflector Sensor Hardware/Software Integration	
David Skalny	<u>Digital Systems for Data Acquisition</u> Mr. Skalny will develop all of the embedded software and digital systems associated with control of the capaciflector sensors. This will include establishing interfaces using a PIC microcontroller that will take data from each sensor module and convert this data into a quantifiable form, such as distance or frequency measurements. Mr.

	Skalny will also work on methods of expanding the sensor array as well as methods of rejecting erroneous data generated by damaged sensors in the array.
Robot Control System	
Craig Pomeroy	<u>Embedded Systems and Robot Autonomy</u> Mr. Pomeroy will primarily be involved with the development of embedded systems that will serve as the source of the robot's autonomy. This will include the programming of a PIC microcontroller so that it can take sensor information from the PIC controlling the capaciflector-based sensors and convert it into a set of directional commands that the robot will follow.
Gary Crum	<u>Software Compatibility</u> Mr. Crum will develop all the hardware and software needed to convert basic directional commands into code executable on the robot's internal computer. This means that Mr. Crum will be responsible for linking the embedded system assigned to Mr. Pomeroy to the robot's on-board computer.

6.0 Summary of Key Intellectual Contributions

6.1 Summary of Key Intellectual Contributions Made by Sean Coleman

Mr. Sean Coleman focused primarily on the capaciflector driver circuit testing and design. Three different capaciflector circuits were evaluated. Mr. Coleman gathered the appropriate parts and constructed the circuits first on a proto-board and then soldered another so that there would be higher reliability and minimizes the possibility of bad connections while testing. Once these circuits were wired, he performed testing it with several different sizes and variations of capaciflector sensors. Mr. Coleman also participated in the testing of the frequency scanning capaciflector driver circuit.

Mr. Coleman was responsible for the design and building of the photo-transistor circuit and LEDs that were used on the robot to aid in the wire tracking. He also troubleshot, corrected, and improved the safety of the 5-volt system that was previously designed and implemented by another team through the used of terminal blocks, polarized connectors, fuses, and wire protective wrap.

6.2 Summary of Key Intellectual Contributions Made by Gary Crum

Mr. Gary Crum focused on creating the schematics and layouts for all of the Printed Circuit Boards (PCB) that where used in this project. This includes designing the layout of the Capaciflector Array Board on a single layer copper clad board, the Feedback Motor Controller, the Communications board and the Data Acquisition Board which were designed for a two layer board and sent out to be manufactured. In addition to designing the hardware for this board, Mr. Crum was involved in creating the software that will run on the Data Acquisition Board and the software that runs on RMS to get the information from the Data Acquisition Board. Mr. Crum also performed extensive testing on the capaciflector array board to fine tune its performance and refining the communication protocol used between the SBC and the Data Acquisition Board. Mr. Crum was involved in some of the initial algorithms used for the autonomous control of the robot which where later replace by a more refined algorithm.

6.3 Summary of Key Intellectual Contributions Made by Austin Matero

Mr. Austin Matero primarily worked on the capaciflector designs in this project, in that his specific task was to develop an advanced version of the capaciflector sensor which could be incorporated into an array structure. Mr. Matero spent the first few weeks researching capaciflector sensors and developing techniques that could transform the basic capaciflector into a more accurate and reliable sensor. Additionally, Mr. Matero conceived the idea to put this sensor on a milled circuit board instead of copper foil. He researched different types of substrate boards to determine the best for the application. He used Sonnet modeling software to create the footprints for this substrate board. Mr. Matero helped to construct the board and test it. This included tests with RF radiation and other interference sources. Mr. Matero used his analog electronics experience to simulate the capaciflector circuit in PSpice to find voltage float problems. Several designs were constructed, and each one was of greater quality. He also worked on several of these versions and determined where the faults were located in the systems. His experience in electronics aided in finding numerous power system problems. Additionally, he worked on repairing circuits which had failed. This included three power supply boards. Mr. Matero also worked on the adding a reverse EMF protection circuit to the motor controllers. Lastly, Mr. Matero tested and bulletproofed the electronics in the system. This included power surge tests, and testing the fuse protection systems.

6.4 Summary of Key Intellectual Contributions Made by Craig Pomeroy

Mr. Pomeroy contributed all code related to the real-time control of the motor system. This involved the entirety of the source code used in the microcontroller within the motor control system, the software running within RMS used within the motor control system, and also the main algorithm governing autonomous wire tracking. He also was responsible for the design of the hardware used to condition the signals from the motor encoders.

6.5 Summary of Key Intellectual Contributions Made by David Skalny

Mr. David Skalny’s original role was to develop all of the embedded PIC microcontroller software and digital systems needed to control and retrieve data from the capaciflector array. This role included examining methods for expanding the sensor array as well as methods of rejecting erroneous data generated by damaged sensors in the array. Under his original role, Mr. Skalny experimented with the use of both I/O expander chips as well as 16-to-1 multiplexers in an effort to reduce the overhead associated with independent capaciflector driver circuitry. Also, Mr. Skalny worked on the development of several pieces of software that applied to the control and retrieval of information from the capaciflector sensors. In particular, Mr. Skalny worked in conjunction with Gary Crum on the creation of the software that would enable and disable capaciflectors in the array in order to prepare them for continuous polling. Additionally, Mr. Skalny was involved in the testing of an existing C code driver for operating both a liquid crystal display (LCD) and a 4X4 matrix keypad off of the same port on the data acquisition PIC microcontroller. The intent of this testing was to allow development of an on-board removable diagnostics module.

In terms of modifications to his original role, Mr. Skalny’s role changed only slightly over the course of the project. As Mr. Skalny’s role in the development of the PIC software overlapped with the PIC communications software development, it was decided that Mr. Crum would handle all of the additional PIC based software which would be responsible for generating frequency information. Mr. Skalny's new role was the development of the SBC software that could interface with functions created by Gary Crum, which were designed to transfer the frequency data in integer form from the PIC to the SBC. In the process of this design, Mr. Skalny set up all of the algorithms needed to allow automatic calibration of the system as well as all of the averaging and comparison software needed to turn the frequency values into their single bit Boolean representation. In order to assure that his software was indeed accurate, Mr. Skalny completed extensive testing on the automatic calibration and data comparison/averaging routines to assure that they could compensate for glitches that might occur when the wire is present under the robot or when the robot is placed on a new type of surface.

In addition to the software outlined above, Mr. Skalny also worked on the creation of additional software at different stages throughout the project in an effort to develop a suite of functions that could aid in the quantification of capaciflector data. The functions included a large set of basic binary imaging techniques for use with binary images. This software was created as a means of dealing with a very large, dense array of capaciflectors as a large enough group of sensors could be used to create a simple binary image. If the capaciflectors could be defined in the sense of a binary image, image preprocessing techniques would have been useful in eliminating noise and determining where the wire lies within the image. The created code included several functions including eight and four neighbor filtering, AND and OR functions, dilation, erosion, closing, and opening functions, and an image segmentation functions. This code was approximately eight hundred lines in length and was designed to function on the SBC versus being a PIC based application. In addition to image processing software, Mr. Skalny developed software that could create a simple interactive model of the robot and its environment in order to validate decision making algorithms in the absence of actual sensor data. Unfortunately, the model was abandoned as it proved to be too simplistic in that it could not model the system accurately enough in situations that involved rotations other that forty-five or ninety degrees.

Mr. Skalny's last key intellectual contribution involved research into the development of frequency-scanning capaciflectors. As this type of capaciflector is at the moment only theoretical, Mr. Skalny had only the device's original patent as a base of reference. Using this document, Mr. Skalny set up and tested the first stage of the system needed to retrieve composition info from the capaciflector. After several days of testing however, the concept of implementing frequency-scanning capaciflectors proved to be infeasible for this project as range issues and compatibility issues with capaciflector structure could not be rejected.

6.6 Summary of Key Intellectual Contributions Made by Derek Sokoloski

Mr. Sokloski started off the semester doing research and development with the capaciflector module. This included constructing many prototypes ranging in size and composition. Key findings involved removing the shield plate from the capaciflector and in many instances there was not a noticeable change in the system. Mr. Sokloski also conducted experiments trying to find the range of the capaciflectors pertaining to footprint. Experimental results suggested a conical field of view where the farthest points of detection of the capaciflectors were centered on the plates. Using this information Mr. Sokloski constructed circular capaciflectors to try to improve the range giving results that differed from the square or rectangular varieties.

The previous semester recommended the need for signal isolation so Mr. Sokloski also conducted experiments where coaxial cable was compared against standard laboratory 26 gauge again giving very similar results with different capaciflector models.

Mr. Sokloski also constructed (soldered) and debugged many of the circuits used though the semester along with aiding in the design of the Plexiglas capaciflector mounting compartment. He also did research on frequency response of the capaciflector grid. Other various experiments Mr. Sokloski helped with included finding a suitable bonding substance (2 part epoxy mix) for the capaciflector grid along with aiding in the physical testing of the capaciflector code.

7.0 Discussion and Suggestions for Future Improvement

The main improvement that needs to be made on this system involves the capaciflector sensor array. Right now, capaciflector technology cannot support small scale capaciflectors. More specifically, the range and accuracy of small sized capaciflectors is simply not sufficient for an advanced boundary tracking system. This fact is particularly evident when considering that the ground clearance of the robot was reduced to about three quarters of an inch. In order to improve capaciflector design, several improvements could be made in both practice and development. The first would be creating an accurate model capaciflector fields using FemLab or another comparable software suite. Also, massive prototyping could occur where variances in plate sizing, types of dielectrics, and separation of plates are exhaustively tested. Also more testing needs to be preformed on the driver circuits to see if they can be modified to better resist stray interference and it increase overall functionality in terms of sensitivity. Also, the construction of an output buffer on the driver circuit to allow for a constant float voltage should be considered. This will create a more standardized waveform from the capaciflectors that will aid in sampling and determination of the frequency. Also, to further test the autonomous algorithms additional optical sensors could be incorporated in addition to the capaciflectors. This would allow the system to be tested with proven and more accurate sensors. Construction of a frequency scanning capaciflector circuit would also be a great improvement. If this technology could be moved from the domain of theory into the domain of reality, determination of materials could be determined though the simple comparison of a test sample to a database of known materials. Lastly, testing noise ratios with larger capaciflectors might help in determining how to produce better versions of smaller capaciflectors.

Some non-capaciflector issues that might also be considered would be the replacement of the wood case with a weatherproof aluminum one. This will allow for greater temperature control and protection against water damage. To allow remote connection to the metal encased robot, the installation of an external wireless antenna or wireless router on the robot might be prudent. The addition of such a wireless antenna on the robot would allow for up to 3 times greater range. An attached router system would eliminate the need for a high voltage power source. Another addition to the robot that could help operators monitor the robot would be the installation of a real-time data monitoring system. For example, it might be useful to relay current, voltage, and system temperature back to the GUI.

8.0 Conclusion

As the future of space exploration requires the need for unmanned missions, automated systems will become necessary. The systems created in this project are backbones for the development of further advancement in automation. Extensive research and testing was required to develop the intelligent systems of this project. The dynamic intelligent motor controller system is shown to be accurate, and modular. The capaciflector research in this project will be used in designing miniaturized low cost sensors. Autonomous algorithms developed in this project can be applied to many applications in addition to the capaciflector and motor control system. Autonomous control was also shown to work with several types of input sensors. Reliability of the entire system was founded from professional PCBs, redundant systems, and in stress tests. In addition to the accomplishments, the designs of the project that did not work will save countless hours of engineering resources in the future. The base systems were proved to be designed for endless applications by the ease of interfacing with other components. Team 2 also showed that team integration was possible by providing the base components needed for their systems to operate. Overall, the full system integration between the sensors, controllers, software, and third party components was shown to be possible, and effective.

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