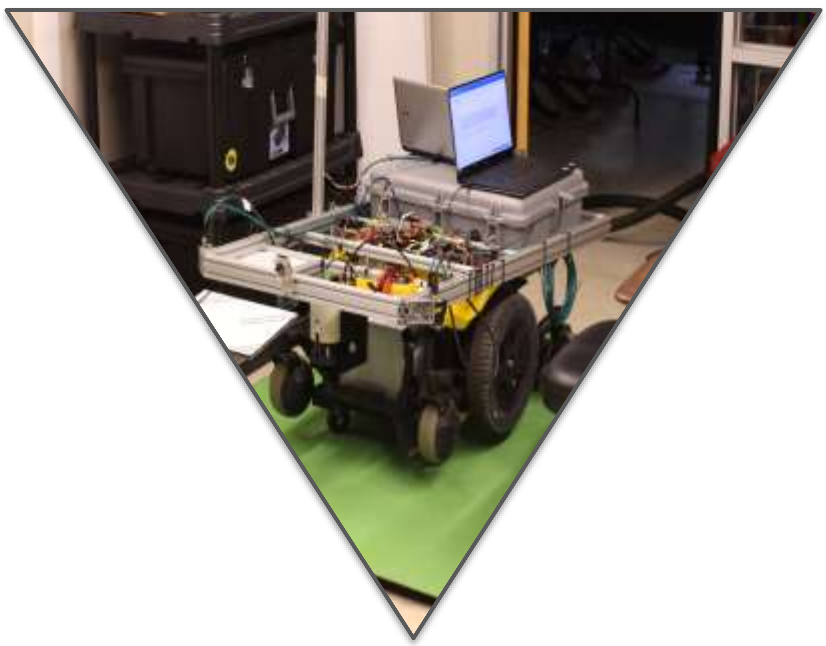
Millersville University of Pennsylvania – Millersville, PA

Autonomous LiDaR-based Environment Navigator

A. Li. E. N.



Design Report

Submitted May 15, 2019

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Introduction

The Autonomous LiDaR-based Environment Navigator (A.Li.E.N.) is a ground exploratory vehicle designed to compete in the 27th Intelligent Ground Vehicle Competition (IGVC) in Oakland, Michigan. The platform is designed to navigate an unknown environment to specific waypoints while avoiding obstacles.

A.Li.E.N. was constructed by the Millersville University Association of Technology, Management, and Applied Engineering (ATMAE) student chapter, known locally as the Millersville Robotics Team, with a total approximate cost of $34,000. Team members are exclusively students at Millersville University, and any MU student is able to join and attend meetings.

As the group is a student chapter of the larger professional organization, organization officers in the following roles manage day-to-day operations:

Officer	Name	Contact
President	Cole Fitch	CTFitch@Millersville.edu
Vice President	William Fern	WHFern@Millersville.edu
Treasurer	Bradford Molchany	BAMolcha@Millersville.edu
Secretary	Robert Kiesel	BobbyK1125@Gmail.com
PR Chair (ad-hoc)	Justin Vipperman, Jr.	JCVipper@Millersville.edu

Statement of Integrity

We hereby certify that the design, engineering, and completion of A.Li.E.N. serves as an experience comparable to a capstone robotics engineering experience. The students featured on this team completed their work without external agents, and were funded by university entities to travel and compete at the IGVC.

Dr. Mehmet Goksu
Faculty Advisor
Professor, Physics

Dr. John R. Wright, Jr.
Faculty Co-advisor
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Team Organization

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		Total Hours	**1200+**	

* indicates concentration in Robotics & Controls Systems, [0] indicates concentration in Nanofabrication Manufacturing Technologies.

Platform Design

Design Assumptions and Design Process

To enable a development process that would both prioritize developing solutions to problems encountered and the flexibility to pivot to any required area, the team combined an Agile development cycle with a Plan-Do-Check-Act (PDCA) continuous improvement cycle.

To design the initial platform and develop the technologies onboard, we adopted an Agile methodology.

Figure 1: Agile Development Cycle.[1]

In our Plan stage, we examined the IGVC rules as a group, proposing possible approaches in an open forum brainstorming session. These proposals were then filtered into a coherent Design, facilitated by our more senior members (typically members who have competed in other competitions, or are on the tail end of their Bachelor's degree. In our Develop phase, we integrated the selected technologies and programmed our systems to interact. This is the stage where most of the late nights were performed. For the Test phase, the team adopted a PDCA continuous improvement cycle to run constantly until the competition date. This cycle ran until deploying the platform for the competition. After the competition, the Review stage will be held in the form of several brainstorming sessions as well as performance review documents, to aid the following years' teams competing at IGVC.

[1] Hadar, Y. (2019). "My Best Tips for Agile Data Science Research." Towards Data Science.

Our PDCA cycle (also known as the Shewhart cycle) features the following stages in continuous improvement: Plan, Do, Check, Act.

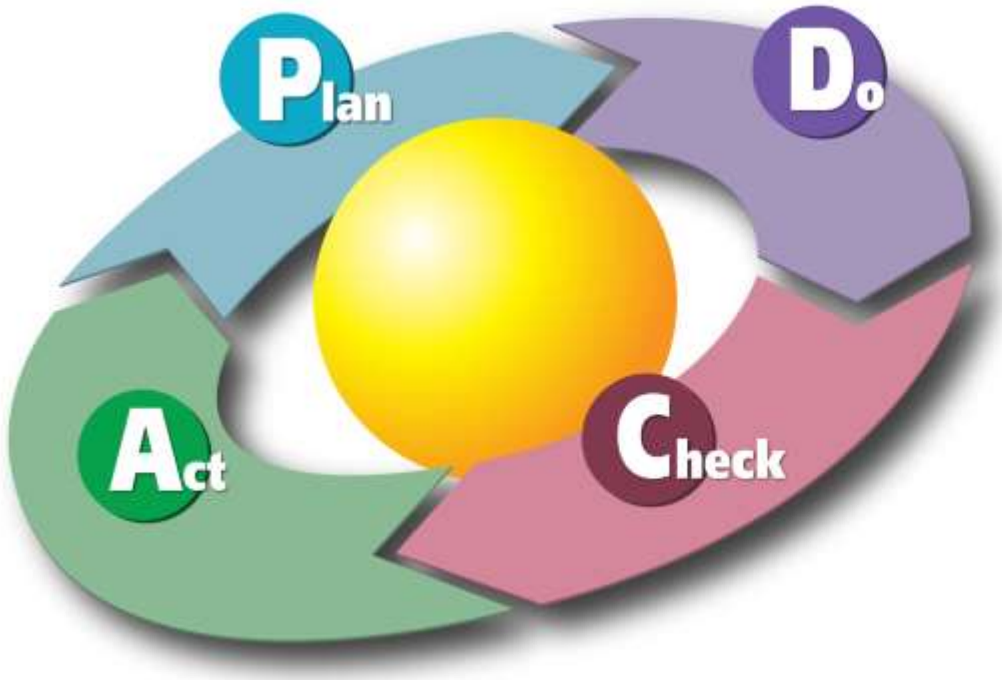

Figure 2: PDCA cycle.[2]

The function of the PDCA Plan step is very similar to the Agile Plan step, but with a key difference: the PDCA Plan is focused on the improvement of a single facet of the platform. Instead of the entire team meeting to plan out the approach to the challenge itself, the PDCA Plan step features several engineers that are process knowledgeable meeting to brainstorm solutions to meet some shortcoming. Following these meetings, assigned engineers will complete the agreed-upon modifications to the platform, and then demonstrate the performance to the entire group. This show-and-tell step allows for the entire team to Check the platform's improvement, as well as propose further changes. Any remaining challenges to the processes are then dealt with in the Act stage before proceeding to Plan once again.

Many tools for ensuring quality were employed, such as Brainstorming, Gantt Charts, Ishikawa/Fishbone diagrams, Statistical Process Control, and Check Sheets. Gantt charts were used to coordinate the development across every facet of the platform. Team members were assigned to certain tasks by the Project Manager, who floated between different development groups to ascertain the progress completed for each task.

Ishikawa/Fishbone diagrams were used to better understand the variables affecting each facet of the platform encountering a problem. The Ishikawa chart

[2] Bulsuk, K. (2009). "Taking the First Step with the PDCA (Plan-Do-Check-Act) Cycle." Karn Bulsuk.

served as both a Cause & Effect diagram as well as a checklist before performing tests.

The Ishikawa diagram features common subsystems and factors that must be considered when troubleshooting the platform's ability to navigate. Each branch can be broken down further into deeper Fishbones, but the above serves as the surface-layer checklist. Due to our usage of quick disconnect wires, a common cause of error was the unwanted disconnect of a wire.

Check Sheets were used in the GPS data logging, where the team conducted measurements of the GPS accuracy against real-world distances. SPC was performed to measure the reliability of the system in measuring to set distances.

Adapted Innovative Concepts + Technology

In many of our engineering- or technology-oriented courses, we tend to prioritize efficiency and speed. Our prior designs for A. Li. E. N. featured a single laptop interacting with the various systems over Ethernet, placing the processing strain on the controlling computer. This centralized computing system may be appropriate for powerful computers, but a slowdown could be experienced if a large amount of data requires processing quickly. Several video streams, a connection to the drive platform, and a GPS subsystem constantly supplying position could quickly bog down even the best of systems.

In order to enable the fastest communication between sensors and the main computational controller, smart sensors were integrated. These are systems that have their own processing power on-board, and complete the data processing before indicating to the central computer that a trigger has been found, typical of distributed control. Our approach to the white lined lane detection consisted of dual machine vision sensors, set to detect contrasts while pointed down. These sensors, typically used for product or barcode inspection, have internal processing capabilities. These are ideal for both industry and low-overhead integration, as the system can be easily connected via its relay outputs and software configurator.

Another innovative approach to our platform is the use of a central microcontroller for drive control and sensor integration. An Arduino-based microcontroller is ideal, as our selected controller features three serial connections for easy integration. In addition, the low-level nature of a microcontroller ensures no extra systems or processes will be running while the system needs to perform.

Mechanical Design

A. Li. E. N. is built on a used Pride Mobility Quantum 614 wheelchair donated by Independent Home Solutions of Lancaster, Pennsylvania. The platform is internally limited to 4.95mph (as indicated on the specification stickers), and can support a maximum human rider weight of 300lbs (136kg) safely. With the removed seat, footrests, and associated components the weight capacity is increased. Shown on the next page is the platform technical drawing with components removed, sourced from the owner's manual. The 14in. (35.56cm) wheels allow excellent surmounting of outdoor obstacles.

Though the wheelchair footrest would provide ample location for the cinderblock, this portion was removed to make room for the sensor suite necessary for environment navigation. Instead, the cinderblock objective is intended to be held on-board the platform, above the battery level.

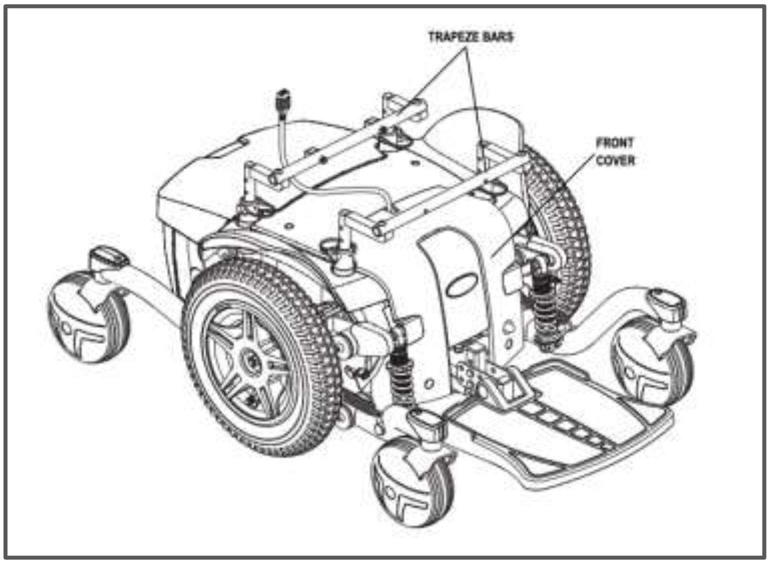

Figure 3: The Pride Mobility Quantum 614.[3]

As shown, the Trapeze Bars mounted to the top of the platform provide an adequate mounting location for the bulk of the platform. The original wheelchair seat would be mounted to these, indicating the bars could withstand considerable weight.

Mounted to the wheelchair base is a frame constructed of 80/20 T-slotted aluminum framing. Polycarbonate sheets were used for panels and mounting electronics to the frame. Additional 80/20 cages with sheeting were constructed to house our machine vision sensors.

Electronic and Power Design

The platform is integrated with a central microcontroller performing the master control. The microcontroller is a Teensy 3.2 powered by an ARM Cortex-M4 at 96MHz. The controller features 32 usable digital I/O pins receiving input from a variety of sensors outfitted to the platform. The controller is programmed in C++, utilizing a modified Arduino IDE. The following diagram is a schematic of the full electronic systems featured. It includes each individual subsystem detailed in this section. The power systems are connected via rails to the +12V, +24V, and GND connections shown across the diagram. These are broken out of the twin 12V batteries, wired together to satisfy the power needs of the platform.

[3] Quantum 614 [Technical Report]. (2009). "Quantum 614 Series Owner's Manual." Pride Mobility Products Corp.

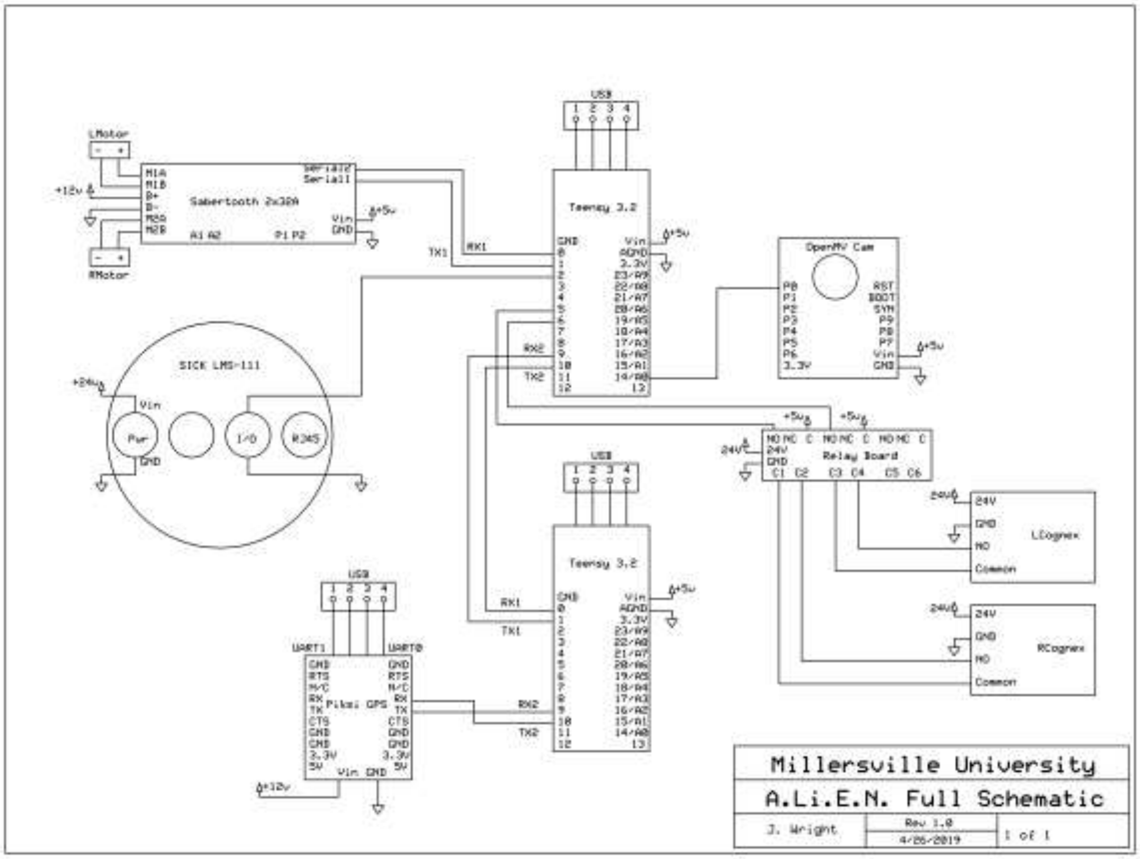

Figure 4: Full electronic schematic.

A Dimension Engineering Sabretooth 2x32A motor controller operates the wheelchair motors using a serial input provided by our microcontroller. The motor controller is wired with dual outputs, ideal for operating the platform. The motor controller is rated at up to 32 amps, which enables the team to use a variety of power sources should it be required.

Twin Cognex Insight 7800 machine vision sensors are integrated on the front corners of the platform. These sensors are industrial cameras typically used to identify items from production lines and any defects detected. The Insight 7800 features a monochrome 640x480 output resolution at 217fps or 800x600 resolution at 165fps. It is powered by 24VDC and has 1000/100/10 Mbps network capability.[4]

The cameras are configurable via Ethernet connection to an on-board laptop. Configuring these cameras consists of training them through Cognex proprietary Insight Explorer software, pictured below. The software allows machine vision engineers to have a concise yet detailed view of the programmed job executed by the camera. The software can be viewed as either a spreadsheet of sensor values or the configuration window, which aids the workflow and connected analysis of outside systems.

[4] Insight 7000 Series. (2019). "Specifications, Insight 7000 Vision Systems." Cognex Corporation.

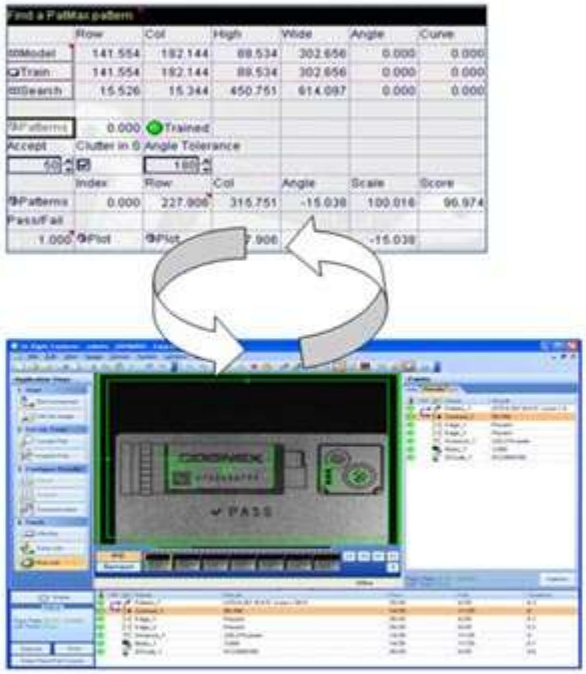

Figure 5: Insight Explorer software view.[5]

The machine vision sensors contain relay outputs, and are connected in series with the 24V battery to trigger a 24V relay. The relay then connects together the Teensy 3.3V power rail to an input pin on-board. This is then read by the command digitalRead(pin). An internal pullup resistor is called through the node INPUT_PULLUP, transforming the input into a Boolean 1/0. A custom-printed circuit board was designed and ordered by our team for a compactly mounted relay bank, shown below.

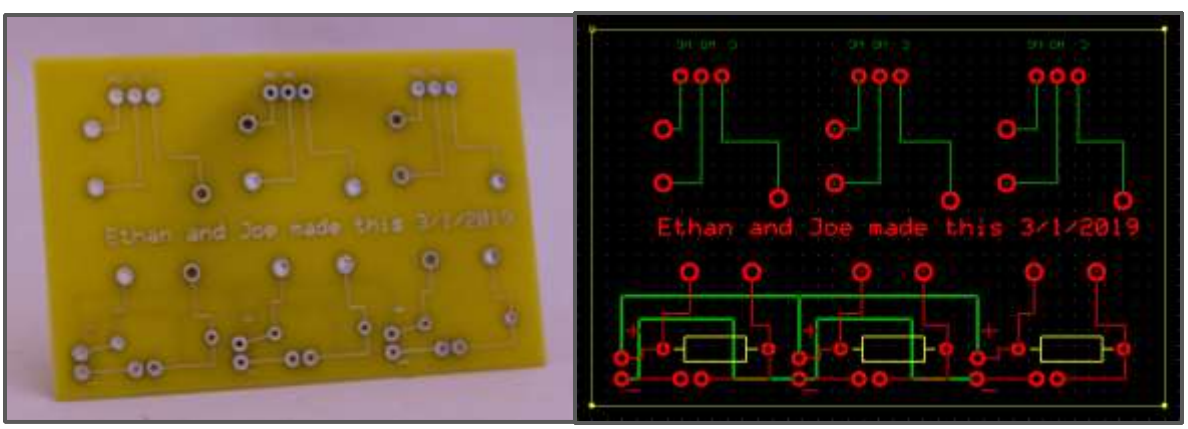

Figure 6: Custom-designed printed circuit board + PCB routing.

[5] Insight Explorer. (2019). "Insight Explorer Software." Cognex Corporation.

The resulting two-layer, no ink screen board was stuffed with Potter & Brumfield 24VDC mechanical relays, connector pins, and resistors.

The platform is guided by a Swift Navigation Piksi Multi GPS. This RTK multi-band receiver features UART serial connections, where it outputs NMEA (National Marine Electronics Association) –compatible serial. This replaces our previous GPS system, an Adafruit Ultimate GPS breakout board. Much of the data-receiving side of the GPS is the same, and the upgrade to the Swift system was as simple as plugging it in. The navigation board is connected via serial to a separated Teensy 3.2 microcontroller, which is connected to the main drive/sense Teensy via serial as well. Our integration prototyping can be seen below on our whiteboards.

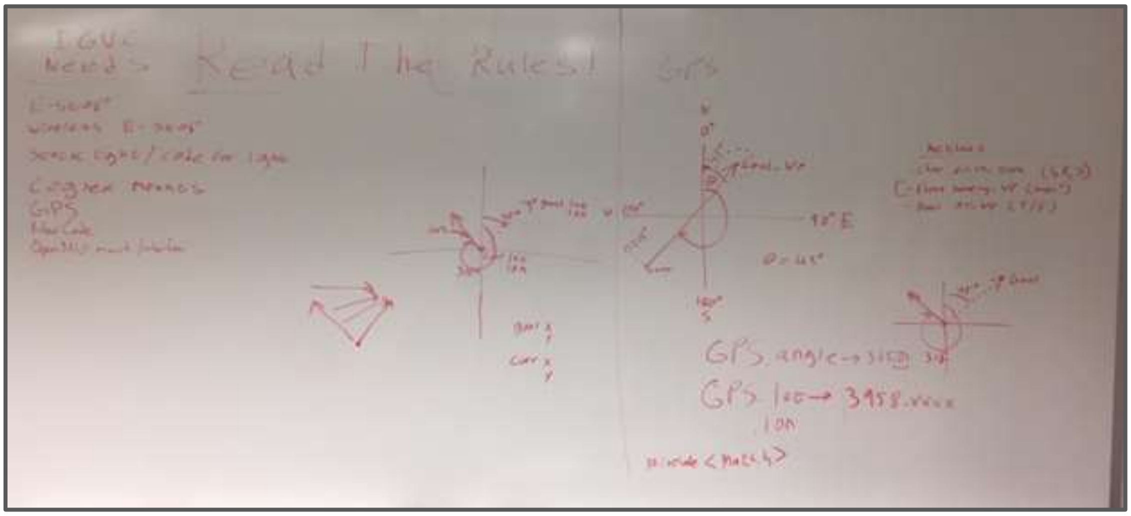

Figure 7: Design-by-whiteboard methodology.

The LiDaR system present on A. Li. E. N is a Sick LMS-111 AIO solution. It is configured over Ethernet, and connects to the Teensy via a relay connection as well. The system is mounted to the front of the robotic platform to sense any approaching obstacles, as seen in Figure 8. The system informs the central Teensy of a forward obstacle, which is then avoided as the microcontroller reroutes the platform's path.

Figure 8: SICK LMS-111

Figure 9: OpenMV Cam M7.[6]

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[6] OpenMV Cam M7. (2019). "OpenMV Cam M7." OpenMV Project.

Mounted on the front of A. Li. E. N is also an OpenMV machine vision camera. This sensor has easily used I/O pins to interact with other electronics, and is programmed using a Python IDE. The sensor can be seen above.The OpenMV Cam has an integrated ARM Cortex M7 processor with a MicroPython OS. The 5V power requirement of the system allows for easy integration with the 5V-supplying Teensy 3.2. The resolution of the camera is limited to standard definition video, though the low bitrate of the video stream is easily processed by the CPU. The usage of a high-definition webcam running from a laptop was explored but the need for I/O pins for integration with the drive microcontroller made this sensor an easy choice.

Network Topology

Updating our systems while on the move is a crucial step to remaining flexible during development. In order to achieve this, we opted to interconnect the smart sensors via Ethernet to a central switch, to which a laptop is connected onboard. This computer is used for diagnostics and reprogramming the smart sensors, and is only used for one task at a time. In addition, the switch used has wireless connectivity enabled, allowing us to remotely connect and reprogram our systems while seated comfortably in-range of the platform.

Figure 10: Network diagram.

Software Strategy

As stated earlier, the Teensy is programmed in a modified Arduino IDE. Normal Arduino C++ libraries can be used in the program design. The GPS system retains our usage of the Arduino GPS library to poll the Swift Navigation Piksi Multi, as both this and our older GPS system communicate via NMEA serial. The library allows for an output of the latitude and longitude of the machine, as well as parsing factors such as altitude, the detected satellite fixes, and the current date/time.[7] In addition, the OpenMV frontward-facing camera is programmed in Python, where OpenCV libraries are used to manipulate the video feed into detecting circular objects.

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[7] Ada, L. (2019) "Arduino Parsing." Adafruit.

Testing and Analysis

Failure Modes, Failure Points, Resolutions

After the decision to use smart sensors, the team opted for the Cognex Checker 4G1 machine vision sensor. This sensor, while familiar to us, is an industrial machine vision sensor no longer manufactured by Cognex. In addition, the Cognex experienced difficulty in differentiating painted contrasted lines from the robot's shadow in grass. For a length of time, the team borrowed past platforms' Checker 4G1s until ordering and receiving twin Cognex Insight 7800 cameras. These newer sensors feature stronger processors and are detailed in the Electronic and Power Design section earlier in this paper. The added brightness of the newer cameras eliminated the contrast issue previously experienced. The availability of the newer camera now enables the team to purchase replacements or have repairs covered by warranty if the sensor fails.

Simulations Employed

To simulate real-time movement of our platform, we utilized our Piksi Multi GPS simulation mode. This function allows us to test our GPS accuracy and performance output without ever leaving the lab. The system outputs a constant stream of GPS coordinates and displays circular motion. The coordinates can be altered on-the-fly, and the serial data streams between the GPS and microcontrollers can be examined with real-world values. This reduced our time-to-deployment while working

Performance Testing to Date

GPS real-world distance testing was carried out using survey markers on an asphalted road outside of our Applied Engineering, Safety & Technology building. Measurements were taken to ensure the test cart traveled 193 inches and output this as a single measurement. At each location, three measurements were made (due to the assumption that the technology would have a high degree of accuracy) and there were five locations surveyed for a pilot study of 15 total data points. This test was carried out to yield an initial understanding of the accuracy of the Swift Piksi Multi GPS, and further tests could be carried out. The left is the resulting Between/Within Capability Sixpack for the pilot study. As shown, the Sixpack is testing the capability for a 1σ test. The tests remained inside the control limits, so the GPS accuracy appears to be in-control. The test garnered a 1.09 Cpk at a span of K = 2, indicating the GPS is 1.09σ capable of meeting the listed

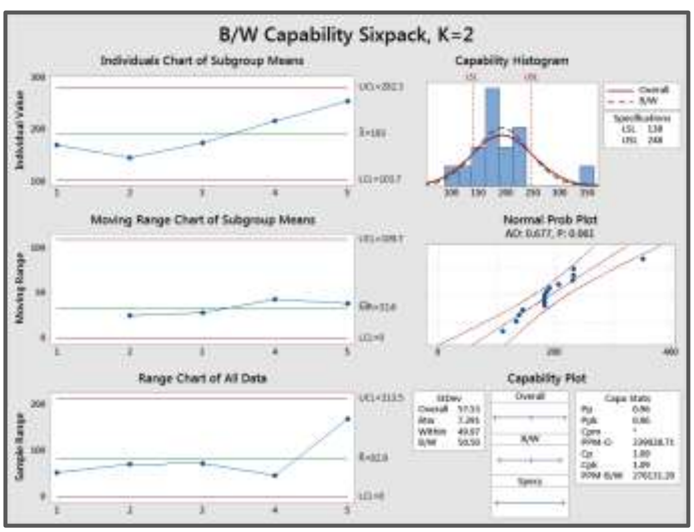

Figure 11: B/W Sixpack Analysis.

specifications. The specifications were varied to examine the point at which the GPS would become 65% confident, or 1σ capable. The span LSL and USL are separated by 110 inches, or 279.4cm. The GPS in the single-board, single-antenna configuration appears to be 65% accurate within 2.794m of its waypoints.

Future Improvements

Mechanical Design

The 80/20 framing allowed for late-stage variation in the platform layout, but a more permanent solution could be implemented for both strength and appearance. During brainstorming, a proposed bent tube steel cage around the outside of the platform could replace the current rectangular frame while increasing structural rigidity in the event of collision. For this replacement, structural simulations and testing could be completed. Furthermore, Millersville University already possesses a steel tube bender, which would be the machine of choice for this upgrade. Potential coatings for the tubes would be either paint or electroplating. The wheelchair platform was quoted at a donation of $5,000, and could be fabricated entirely from material if cost were an issue.

Electronic and Power Design

Though the platform features a robust power delivery system from the twin 12V batteries, a transition to a single 24V Smart Battery-brand system could be explored. The desired power system would reduce the battery footprint considerably, allowing the cinderblock to be mounted beneath the platform. This upgrade carries with it a large price tag, as well as a considerable lead time for orders from the Smart Battery manufacturer, so this must be taken into account for the planning stage of upgrades. In addition, the electronics amounted to just over $28,000, so future cost-reductions would benefit reproducibility.

Future Testing

Additional testing is recommended for each system and function installed on A. Li. E. N. Performance testing that could be included in future iterations could involve identification defect testing with the Cognex Insight 7800 sensors, where a complex object could progress through the detection range on a conveyor. For each object detected, a pass is recorded. For each failure, a fail is recorded. The operator would then explore improving the reliability of the detection. Furthermore, the sensors are able to output a confidence level of detection. This value could be logged overtime for both correct parts and incorrect parts to better test the platform's ability to make decisions and narrow the threshold for allowable detections. Then, a Sixpack analysis could inform the operator of the reliability of the system to detect the painted lines under varying conditions.

List of Figures

References

Ada, L. (2019). "Arduino Parsing." Adafruit. Retrieved from https://learn.adafruit.com/adafruit-ultimate-gps/parsed-data-output.

Bulsuk, K. (2009). "Taking the First Step with the PDCA (Plan-Do-Check-Act) Cycle." Karn Bulsuk. Retrieved from https://www.bulsuk.com/2009/02/taking-first-step-with-pdca.html.

Hadar, Y. (2019). "My Best Tips for Agile Data Science Research." Towards Data Science. Retrieved from https://towardsdatascience.com/my-best-tips-for-agile-data-science-research-b40365cc979d.

Insight 7000 Series. (2019). "Specifications, Insight 7000 Vision Systems." Cognex Corporation. Retrieved from https://www.cognex.com/products/machine-vision/2d-machine-vision-systems/in-sight-7000-series/specifications.

Insight Explorer. (2019). "Insight Explorer Software." Cognex Corporation. Retrieved from https://www.cognex.com/products/machine-vision/2d-machine-vision-systems/in-sight-vision-software.

OpenMV Cam M7. (2019). "OpenMV Cam M7." OpenMV Project. Retrieved from https://openmv.io/products/openmv-cam-m7.

Quantum 614 [Technical Report]. (2009). "Quantum 614 Series Owner's Manual." Pride Mobility Products Corp. Retrieved from https://www.pridemobility.com/pdf/owners_manuals/us_jazzy/us_quantum_614_om.pdf.