Progress Report for an Autonomous Robot

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Executive Summary

Axiom Electronics is a manufacturer of high-end electronic circuit boards for both new assemblies and for older machines that require replacement boards. During the course of the production process, valuable time and energy is wasted because an assembler must push a cart from point A to point B. Axiom Electronics would like to free up the assembler by having a robot to do this job.

This report covers recent progress that has been made in the creation of a robot that would successfully relieve the assembler of its current transport duties. External and internal research has paved the way for the team’s building efforts. After examining various designs, a design decision matrix was created to guide the team in making a good decision. Once a final design was settled upon, the team has started to select individual components of the robot. This report also covers how the project timeline is progressing and how the project meets or exceeds the sponsor’s expectations.

The main specifications for the robot include a minimum velocity of 50 feet per minute, a maximum load capacity of 80 pounds, the ability to navigate 35 inch wide hallways, a 24 inch by 36 inch shelf, and autonomous navigation.
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1. Introduction

Axiom Electronics is a manufacturer of circuit boards for new and existing technology. During manufacturing, products need to be moved from one part of the factory to another. Traditionally, this has been done by an assembler. To cut costs, they would like to purchase a robot to perform this task. After investigating commercial robots however, they could not find one that would fit in their price range. Because of this they decided to contact Portland State University and have a capstone team create the device. The robot needs to autonomously navigate on the factory floor to pre-determined points. It must move through corridors 35 inches wide, be safe around humans, and avoid obstacles. It must travel with a minimum velocity of 50 feet per minute, have the dimensions of 36”x24”x30”, and have a payload of 80 pounds. All of this is to be done with a budget of $10,000.

2. Mission Statement

To develop an autonomous robot that is capable of transporting electrical circuit boards inside Axiom Electronics’ manufacturing site. The robot must carry at least 80 pounds of material at a speed of at least 50 feet per min. The robot must travel between specified points while avoiding humans and other various obstacles. Its loading platform will consist of two 22.5”x17.5” rectangular holding bins which will carry the components that needed to be moved..

3. Project Planning

An initial project timeline was created in early January and since then it has undergone multiple alterations. Issues with the in-depth nature of the project, as well as the unforeseen knowledge base required to accomplish the project have led to the postponing of some important decisions such as the chassis design and the selection of the motor and the wheels. The Gantt chart below represents the current project timeline. The design team is presently working on finalizing the list of items that need to be purchased. This list includes: the steel necessary to weld a chassis, the driving wheels, the caster wheels, and the specified motor. We hope to have an initial prototype completed by early April, perform evaluation and testing on the prototype between April and May, and move the product to the customer’s facility in June.
Table 1 - Project Timeline. Green items represent tasks that are completed. Purple are tasks that have been delayed. Red are tasks that have yet to be completed.
4. PDS Summary

Development of the Product Design Specifications occurred in conjunction with the external search and exploration of the project’s feasibility. During that time, the team was not fully aware of the full extent of what the this project would entail. As a result, the initial PDS was not as sufficiently specific. The full PDS table can be found in Appendix A and the main highlights are included here:

- **Velocity** - The robot should move at a speed between 50 and 100 feet per minute.
- **Payload** - The robot must be capable of carrying at least 80 pounds on a 36 inches by 24 inch shelf.
- **Maneuverability** - The robot must be able to maneuver in a 35 inch hallways.
- **Environment** - The robot must be able to autonomously navigate from one point to another. The robot’s navigation system must include obstacle detection capabilities that will stop the robot from colliding with obstacles and/or a program to navigate the robot around obstacles.
- **Safety** - The robot must be safe around humans. Thus, the robot may be outfitted with a flashing light to alert the assemblers of its presence and must be able to stop if it senses a human in its path.

5. External Search

At first, the team conducted a search for existing products that fulfilled the robot’s design requirements. From this search process, we discovered some current robot design features that could be utilized in our situation. Packmobile — a company that specializes in automation solutions — showcases an automated guided vehicle (AGV) that is able to transport packages, boxes, or parts inside a manufacturing site. Figure 1 shows the basic structure of this product. While the Packmobile design is a good example to refer to, it requires an invisible fluorescent guidepath that is not applicable to this project since Axiom requires that no guidepath markings

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[http://www.egeminusa.com/pages/agvs/agvs_packmobile.html]
be made on their production floor. Another AGV from Savant Automation\(^2\) was also considered. Savant Automation uses inertial guidance which can adjust the floor plan easily by means of software programming. This navigation technology is a close approximation to our project’s intended design since it satisfies Axiom’s floor specifications.

Our external search involved reading through books such as “Introduction to Autonomous Mobile Robots” published by MIT Press. MIT’s “Introduction” gave an overview of the design and manufacturing process for a mobile robot and helped us to develop our detailed design. Specifically, our external search led us to include the chassis design, the material selection, the motor selection, the wheel selection, and the electrical and control design.

One of the most important features of our robot is the ability to self-navigate on the floor. Therefore, we conducted an external search of indoor-positioning technologies. While most of the wireless technologies for positioning are affordable and easy to install, the sensor’s accuracy will only bring the robot within 50 cm of its desired location. Ubisense, a leading company in indoor navigation systems, offers a real-time indoor navigation system with an accuracy of 30 cm. Unfortunately, Ubisense’s system requires a 24/7 server and costs $12,500 above our project budget. The inability to utilize Ubisense’s technology necessitated exploring other solutions that offered acceptable accuracy at a cheaper price.

6. Internal Search

Internal research first focused on the feasibility of the project. Given the nature of the programming requirements and the relative inexperience of the capstone team, feasibility was a major concern both to the team and to Axiom Electronics. Thus, a graduate student was assigned

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to perform the programming and select the robot’s necessary electrical components.

The next step in this project was to design the chassis and to select the robot’s mechanical components. Before the chassis could be designed, however, wheel arrangement options had to be examined. First, we considered a triangular wheel configuration that relied on three powered, omnidirectional wheels. The triangular design was rejected because the omnidirectional wheels would be difficult to program and because the triangular base would be unstable. Second, we considered a rectangular shape with four wheels, two of which were powered and two of which were passive. Because the four-wheel base offered maximum maneuverability and stability, we decided to use this design. The initial configuration of this design is shown in Figure 2. While this design provides maximum stability, maneuverability would be minimal. Figure 3 depicts a configuration in which the active wheels are located in the middle of the chassis, providing maximum maneuverability but less stability than the schematic in Figure 2. To enhance stability, nubs were added to each corner.
7. Final Design Evaluation

To assist with the chassis selection, the Design Selection Matrix in Table 2 was created. Wheel placement affected three criteria: stability, maneuverability, and ease of use. Performance characteristics were rated in terms of how well the robot would perform under each given configuration. Table 2 is the Design Evaluation Matrix and shows that the trapezoidal chassis will perform slightly better than the rectangular chassis.

Table 2 - Design Evaluation Matrix

<table>
<thead>
<tr>
<th>Concept</th>
<th>Criteria</th>
<th>Weighted Value</th>
<th>Criteria</th>
<th>Weighted Value</th>
<th>Criteria</th>
<th>Weighted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stability</td>
<td>5</td>
<td>Manueverability</td>
<td>3</td>
<td>Ease of use</td>
<td>4</td>
</tr>
<tr>
<td>Triangular</td>
<td>2</td>
<td>10</td>
<td>4</td>
<td>12</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Rectangle</td>
<td>5</td>
<td>25</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>4</td>
<td>20</td>
<td>5</td>
<td>15</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Total Value</td>
<td>55</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td>36</td>
</tr>
</tbody>
</table>

In terms of the criteria for the automated car, stability was weighted as the highest priority and maneuverability was weighted as the second highest parameter. Lastly, ease of use was weighted as the least important consideration. The rationale behind this weighting arrangement was that stability would play a significant role in the loading and unloading of the cart. Thus, if stability was jeopardized, catastrophic damage to the sponsor factory floor could occur. The stability of the robot, given outside influences such as collisions and quick deceleration, were also examined.

In the same way, maneuverability was considered a necessity because Axiom Electronics has limited space for the cart to operate on the factory floor. Out of the three best designs that were considered, the trapezoidal configuration best allowed for a 360-degree rotation. This configuration maximizes torque and maneuverability by allowing the wheels in the center to drive and steer the cart.

Finally, our design matrix examined ease of use. We found that the triangular consideration would be unstable and unsafe for working conditions at the factory. By contrast, the rectangular configuration was easy to use. Our last design consideration does not carry the
significant weighted value because the system needs to be monitored and evaluated to make sure that no tipping occurs. The four wheel configurations also allows for compensation in different loads where the trapezoidal design is lacking. This will ensure that the weight is evenly distributed across the shelf and thus prevents tipping.

8. Detailed Design

The design of the robot has broken down into four main categories: the chassis design, the material selection for the robot, the selection of the wheels, and the selection of the motor.

8.1. Chassis Design

Three different factors influenced the final design of the chassis--wheel placement, affordability, and the manufacturability of the chassis. Figure 4 is a model of the chassis in Abaqus. It was modeled using 1”x1”x0.165” steel square tubing. Two drive motors will be placed at the center of the robot on the sides, and one caster wheel will be placed on either side of the motors at the edge of the robot. This setup provides maximum maneuverability. Since this configuration is less stable, nubs will be placed on each corner to keep the robot from tipping.

After a final design was settled upon, Finite Element Analysis was performed to ensure that the chassis would not fail during service. The maximum stress is well under the ultimate strength of the material.

![Figure 4 - Model of the final chassis design in Abaqus](image)
8.2. Material Selection

We identified two final candidates for the material for the chassis: square steel tube and 80/20 aluminum T-slotted profiles. To help in deciding between these two options, we created an advantages - disadvantages tables for both materials as can be seen in Table 3.

Table 3 - Pros and Cons of using Steel versus 80/20 Aluminium

<table>
<thead>
<tr>
<th></th>
<th>Square Steel Tube</th>
<th>80/20 Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- Easy to be welded&lt;br&gt;- Easy to be modeled and analyzed using Abaqus and Solidworks&lt;br&gt;- Inexpensive (only about $150 in total)&lt;br&gt;- Able to withstand 80lbs, small deflection.</td>
<td>- Light-weight&lt;br&gt;- Good-looking&lt;br&gt;- No welding needed (brackets, bolts and nuts required)&lt;br&gt;- Support team from the 80/20 company to help calculate deflection.&lt;br&gt;- Able to withstand 80lbs, also acceptable deflection.&lt;br&gt;- Easy to modify the position of the shafts, even after the robot has been completed.</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>- Heavier than 80/20 aluminum.&lt;br&gt;- Not able to modify after welding.&lt;br&gt;- Our lack of experience in welding =&gt; it is possible to ruin the material.</td>
<td>- Too expensive ($500 in total)</td>
</tr>
</tbody>
</table>

In the end, we decided to use steel for the chassis because of our limited budget. The steel will be rectangular tubing with 1.000 x 1.000 x 0.083 dimensions.

8.3. Wheel Selection

For this product, two different types of wheels are required--one for the caster wheels and the second for the driving wheels.
8.3.1. Motor Wheels

In order to ensure that the robot can overcome obstacles such as floor mats, wires, etc., a six-inch diameter wheel has been chosen. This diameter reduces the torque necessary to operate the wheel in comparison to a larger wheel. The driving wheel is made of soft rubber and does not rely on air. Using soft rubber makes the wheel more shock absorbent and thus creates a smoother ride without the necessity of a driving wheel suspension. By not relying on air, there is a less frequent need for tire maintenance.

8.3.2. Caster Wheels

In order to maintain uniformity throughout the robot wheels, the team selected six inch diameter casters. Unlike the drive wheels, the caster wheels require a suspension system. The system was analyzed using vibrational analysis to determine whether or not the spring constant and damping ratio required for the system to maintain smoothness. The two models used to approximate a real-world analysis are depicted in Figures 6 and 7. Figure 6 shows a scenario
where the motor wheels act like a pivot point. The system can then be treated as a One Degree of Freedom system. This is the most realistic of scenarios since the wheels will have a higher spring constant the caster wheels will. Figure 7 shows a scenario where the motors do not act as a pivot, this is a Two Degree of Freedom System. This would be applicable is the chosen driving wheels have a very soft spring constant.

After selecting the natural frequency and damping ratio ranges, the spring constant and the damping were chosen and analyzed to ensure they fit in the appropriate ranges.

8.4. Motor Selection

The motor selection process requires the consideration of many aspects such as mechanism of connecting motor and driving wheel, speed profile of the motor during its working cycle, the supplied power, and various other parameters. At the beginning of the process, some motor-related parameters were specified as below:

- Weight of the robot: no load - 60 lbf, 100% load - 140 lbf.
- Maximum Speed: 100 fpm or approximately 80 rpm with 6 in diameter wheel.
- Time to accelerate: 1 s.
- Provided voltage: 12V or 24V, battery pack.

Next, the working scenario of the motor was assumed as in Figure 8. The maximum required torque and average torque are approximately 6.7 and 3 N-m respectively. The detailed calculation of these torque values can be found in Appendix B.
After calculating torque values, a search for suitable motors and gearheads was conducted with the assumption that the motors and gearheads are connected directly to the driving wheels. A suitable motor should have its nominal speed and torque greater than its maximum speed and torque. In some cases, the maximum torque required can stay outside of the continuous working region of the motor, but it might affect the lifespan of the motor itself. Other parameters that were also considered during the selection process of the motor are the maximum axial load and radial load that the gearhead can support. Currently, we are looking for motors and gearheads from different suppliers. We are looking at an Allied DC gearmotor (model number RA-DTPL-36DR-18-00) as specified in Table 4, but we are costing out the product before making a purchase decision.

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA-DTPL-36DR-18-00</td>
</tr>
</tbody>
</table>

8.5. Electrical Design

Since the graduate student is heading up this portion of the project, we have limited knowledge about the electrical design. However, the following devices will be needed for the robot to navigate:

- Microcontroller
- Ultrasonic sensors
- Laser-range finder
- Accelerometer
- Power system

Also, encoders will be purchased if the motors do not already have built-in encoders.
9. Conclusion and Recommendations

The purpose of this report is to outline all progress that has been made on this project. At this point, we have conducted external and internal research, finalized a chassis design, almost finished the final selection of the motors and gearbox, and made significant progress on the suspension design. The project is 11 weeks from completion and the tasks remaining include ordering the chassis material and finalizing the suspension for the caster wheels. Currently, we are on track to fulfill all of the minimal requirements set by Axiom. The project has gotten slightly behind schedule, but the team is working hard to get back on track. Overall, while some tasks are not progressing as planned, the project is going smoothly.
## Appendix A - PDS Table

Table A1 is the PDS table for the product. Initially, it was written early in the project timeline but has been revised to include current information.

*Table A1 - PDS Specifications for the product.*

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Requirement</th>
<th>Customer</th>
<th>Metrics</th>
<th>Target</th>
<th>Basis</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Priority</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment (navigation)</td>
<td>Ability to Navigate around obstacles</td>
<td>Axiom Electronics</td>
<td>Collisions and accidents</td>
<td>No Collisions or accidents</td>
<td>Interview with AE</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Laws, Codes, and Standards</td>
<td>Environmentally Responsible</td>
<td>State</td>
<td></td>
<td></td>
<td>Regulations</td>
<td>Careful study</td>
</tr>
<tr>
<td>Documentation (customer)</td>
<td>A Users Manual</td>
<td>Axiom Electronics</td>
<td>Instructions</td>
<td>Well Written</td>
<td>Capstone Decision</td>
<td>Careful Validation</td>
</tr>
<tr>
<td>Time Scale</td>
<td>Finish work based on the timeline given</td>
<td>Capstone Group</td>
<td>Date</td>
<td>Finish before June 10.</td>
<td>Discussed within group</td>
<td></td>
</tr>
<tr>
<td>Performance (battery)</td>
<td>The battery lasts for a work period</td>
<td>Axiom Electronics</td>
<td>hours</td>
<td>8</td>
<td>Axiom Electronics</td>
<td>Testing</td>
</tr>
<tr>
<td>Performance</td>
<td>Motor works as required</td>
<td>Capstone Team</td>
<td>mN-meters</td>
<td>6,772</td>
<td>Calculations</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Performance</td>
<td>Robot doesn’t excessively vibrate</td>
<td>Capstone Team</td>
<td>Cycles of Vibration</td>
<td>&lt;3</td>
<td>Group Decision</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Size and Shape</td>
<td>Follow prescribed dimensions</td>
<td>Axiom Electronics</td>
<td>Inch</td>
<td>36” x 24” x 30”</td>
<td>Axiom Electronics</td>
<td>Measurement and Design</td>
</tr>
<tr>
<td>Retail and production costs</td>
<td>Remain within Budget</td>
<td>Axiom Electronics</td>
<td>Dollars</td>
<td>$10,000</td>
<td>Axiom Electronics</td>
<td>Budget</td>
</tr>
<tr>
<td>Testing</td>
<td>The robot works to specifications</td>
<td>Capstone Group</td>
<td>Robot</td>
<td>Carries weight</td>
<td>Group Decision</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Safety</td>
<td>Does not harm anyone</td>
<td>Axiom Electronics</td>
<td>Injuries</td>
<td>No Injuries</td>
<td>Axiom Electronics</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Criteria</td>
<td>Requirement</td>
<td>Customer</td>
<td>Metrics</td>
<td>Target</td>
<td>Basis</td>
<td>Verification</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------------------------------------------</td>
<td>------------------</td>
<td>------------------</td>
<td>--------</td>
<td>---------------------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td><strong>Medium Priority</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Life Span</td>
<td>Continued Operation for the foreseeable Future</td>
<td>Axiom Electronics</td>
<td>Years</td>
<td>5</td>
<td>Interview with AE</td>
<td>Parts and Processes Analysis</td>
</tr>
<tr>
<td>Environment (floor)</td>
<td>Ability to work in factory setting</td>
<td>Axiom Electronics</td>
<td>Have grip on floor surface</td>
<td>Be able to turn &amp; stop</td>
<td>Interview with AE</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Installation</td>
<td>Quick Installation</td>
<td>Capstone Group</td>
<td>Day</td>
<td>&lt;1</td>
<td>Brainstorm Decision</td>
<td>Processes Analysis</td>
</tr>
<tr>
<td>Legal</td>
<td>Not conflict with existing patents</td>
<td>Axiom Electronics</td>
<td>NA</td>
<td>NA</td>
<td>Design Decision</td>
<td>Careful Study</td>
</tr>
<tr>
<td>Documentation (university)</td>
<td>PDS Document, House of Quality</td>
<td>Capstone Group, Dr. Yi</td>
<td>1 each</td>
<td>Required by the department</td>
<td>Submitted to the professors</td>
<td></td>
</tr>
<tr>
<td>Quality and Reliability</td>
<td>Fulfills product expectations</td>
<td>Capstone Group</td>
<td>NA</td>
<td>NA</td>
<td>Brainstorm Decision</td>
<td>Testing</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Should be easy to maintained</td>
<td>Axiom Electronics</td>
<td>times per year</td>
<td>2</td>
<td>Axiom Electronics</td>
<td>Checking performance twice a year</td>
</tr>
<tr>
<td>Performance</td>
<td>Velocity</td>
<td>Axiom Electronics</td>
<td>Feet per Minute</td>
<td>100</td>
<td>Axiom Electronics</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td>Performance</td>
<td>Ability to Navigate narrow hallway</td>
<td>Axiom Electronics</td>
<td>Inches</td>
<td>&gt;35</td>
<td>Axiom Electronics</td>
<td>Testing and Validation</td>
</tr>
<tr>
<td><strong>Low Priority</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>Be Lightweight</td>
<td>Capstone Group</td>
<td>Pounds</td>
<td>&lt;50</td>
<td>Brainstorm Decision</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Chassis Weight</td>
<td>Be transportable</td>
<td>Capstone Group</td>
<td>Pounds</td>
<td>Less than 50</td>
<td>Brainstorm Decision</td>
<td>Testing</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Worthy of showcasing</td>
<td>Axiom Electronics</td>
<td>Looks Good Customer Feedback</td>
<td>Artistic choice</td>
<td>Interviewing the customers</td>
<td></td>
</tr>
<tr>
<td>Manufacturing Facility</td>
<td>A place with enough tools and machines to manufacture</td>
<td>Capstone Group</td>
<td>A clean Room</td>
<td>The capstone lab</td>
<td>Group Decision</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>
B - Torque Requirement Calculations

The following is an analysis of the torque output required by the motors to be selected.

Summary: In order to choose a motor, we calculated the maximum torque and mean torque required. All calculations utilizing the procedure from the Department of Mechanical and Aerospace Engineering at the University of Florida.

Analysis:

Given: A robot weighing 140 pounds needs to be accelerated over the course of 1 second to a velocity of 100 feet per min.

Find: A motor that will fulfill the requirements.

Assumptions: The floor is made of concrete, the wheels are made rubber, and the robot is traveling up an inclination of 3 degrees (worst case scenario).

Solution:

Figure B1 is a schematic showing the free-body diagram of the forces acting on the robot in motion. TTE is the Total Tractive Effort.

\[
TTE = RR + GR + FA
\]

where RR: Rolling resistance.

GR: Gravity Resistance.

FA: Force due to Acceleration.

TTE: total force required to accelerate the robot.

\[
RR = GVW \times C_{rr}
\]

where GVW: Gross Vehicle Weight (140 pounds),

\[C_{rr}\] is the rolling resistance which was set at 0.02
\[ GR = GVW \times \sin(\alpha) \]

where \( \alpha \) is the angle of inclination. (3 degree)

\[ FA = GVW \times V_{\text{max}} / (g \times t) \]

where \( V_{\text{max}} \): maximum velocity

\( t \) is the time it takes to accelerate to \( V_{\text{max}} \)

Total Torque is determined by:

\[ T_w = \text{TTE} \times R_w \times RF \]

where \( R_w \) is the radius of the wheel and \( R_f \) is the resistance factor. Since there are two drive wheels, the TTE in this equation is per a wheel.