# Designing a Simple, Robust, Precision Robotic Platform for Medium Quantity Production

by

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## ABSTRACT

A niche which has yet to be saturated in the growing market of educational and research robotic platforms is the mechanically-simple, electronically-powerful research robot. Useful in fields such as algorithm and artificial intelligence research, such a robot would support a variety of sensor configurations and run both precisely and autonomously. Such a robot requires a robust, simple, preassembled mechanical platform; an electronics system which easily accepts a variety of sensors; and user friendly computer interface. This paper follows the design of a drive system and chassis for such a robot. Although the prototype developed did not meet the specifications of \$250-\$500 selling price for five hundred units, data was gathered from the prototype which will allow for a more cost effective redesign.

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# 1 INTRODUCTION

The growing market of educational and research robotic platforms has yet to be saturated. Two unfilled or under-filled niches have been identified. One is an introductory robot which provides a quick, engaging way for kids to get interested in the programming aspect of robotics without the mechanical complexity of most kits. A prototype of this educational robotic platform has already been made by Ross Glashan and John Rebula using modified servo motors and a laser cut acrylic base. The second is a research robot which supports a variety of sensor configurations and which runs both precisely and autonomously based on its input, useful in fields such as algorithm and artificial intelligence research. These two robots have several similar requirements – they both call for a robust, simple, preassembled mechanical platform; an electronics system which easily accepts a variety of sensors; and user friendly computer interface. The more expensive research robot platform can be designed as an upgraded version of the original educational prototype, reusing most of the non-mechanical systems. Since the software and electronics have already been designed, they will be discussed only in passing. The three main differentiations between the versions are a motor upgrade with the addition of an encoder for precision in speed, a more professional chassis, and more flexible options for motor set up.

I was able to find only one direct competitor with comparable levels of mechanical simplicity and electronics and software versatility, which is the Khepera line from K-Team Corporation. A Khepera robot costs about $1350 – in this case the goal is to design a robot which runs between $250 and $500. Initial production is estimated to be about one hundred robots with the goal of scaling up to one thousand units per year. I used five hundred units for my cost analysis because one hundred is overly affected by start up costs, while one thousand is not affected enough.

# 2 COMPONENT SELECTION

## 2.1 MOTOR, GEARBOX, AND ENCODER

I decided on a DC motor with graphite brushes for a combination of price, reliability, and simplicity in control systems. I employed two methods to estimate the specifications for the motor: a comparison to the motor used for the educational robot and back-of-the-envelope calculations of motor requirements. The servo used for the lower-grade model had a stall torque of .42 Nm and a no-load velocity of 50 rpm. Although the newer version will be larger and have a higher maximum speed, these values give a rough estimate of the range into which the motor should fall. Then I used quick calculations to derive approximate desired performance standards for the research robot. Assuming the top speed of the robot is around 1 m/s and the wheel is .05 m in diameter, the velocity of the motor will be around 400 rpm while loaded. While eight times the no-load speed of the original

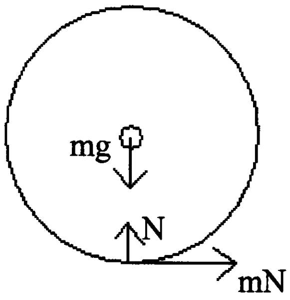


Figure 1: The free body diagram shows that the approximate maximum torque provided by the motor will be the product of the weight of the robot, the radius of the wheel, and the rolling friction between the wheel and the surface it's driving on.

motor is excessive, an operational velocity of 150-200 rpm is ideal. For the torque calculation, I examined a worst-case scenario involving a 50 N robot turning using only one wheel, with a wheel of radius .025 m and a rolling coefficient of friction at m=.5. The resulting required torque is .625 Nm, approximately one and a half times the stall torque of the educational robot's servo. I looked for a motor capable of providing .625 Nm of torque and with a continuous torque on par with the servo motor's stall torque.

This range of torque and speed requirements is most easily achieved by adding a gearbox. Given the constraints of keeping the robot at a manageable size while including a motor, gearbox, and encoder, I looked for a company offering motors in this performance range and the option to integrate these three components. Using the online search engine GlobalSpec (www.globalspec.com), I discovered that Maxon Motors USA provided these functionalities. Their gearboxes cannot take inputs higher than 8,000 rpm, so the highest reduction which will be useful is 53:1 to go from 8000 rpm to 150 rpm. The 53:1 gearbox is planetary with an efficiency of 59%, so the continuous torque of the motor must start at 13 mNm, with a stall torque of at least 20mNm. The A-max 26 110960 fits these requirements – the maximum speed is 10400 rpm, the no load speed is 8010 rpm, the stall torque is 66.6 mNm, and the maximum continuous torque is 14.2 mNm. It also has graphite brushes, which are preferable in high torque applications. I selected this motor for these reasons; however, given that I was cautious with my estimations of required torque and speed, it is likely that the motor is more powerful than necessary. This can be tested with the prototype; current usage can be gauged to evaluate torque requirement and voltage curves can help determine if a slower maximum speed is useable.

The chosen encoder is the least expensive one that Maxon Motors sells for the 26 mm diameter motor. This encoder, the 225778, also has the smallest foot print, having the same diameter as the motor. Since this encoder takes six to eight weeks to deliver, for the initial prototype I used a different, larger, more expensive encoder with similar operational specifications.

## 2.2 BATTERY

The motor requires a 12 V battery. The next specification to determine is the capacity of the battery. At the maximum continuous torque, the motor draws 1A of current. 2A is therefore a conservative estimate for average operating current – on the one hand the motors will normally be running at less than the maximum continuous torque, but on the other hand the electronics may draw low current, but still not zero, and occasionally the torque may peak above the maximum continuous torque. The capacity should be as large as possible, with the minimum being one hour of continuous rigorous use, or 2 Ah. Two more parameters play significant roles in battery selection – price and size. At least one dimension should be considerably less than three inches to fit the packaging requirements of the robot. Under that constraint, weight does not become significant factor. Nickel-metal hydride and nickel-cadmium batteries which fit these specifications cost around $70-$100 dollars a piece. Lead-acid batteries are about half the cost for the same specifications. The battery I chose, the Yuasa NPH3.2-12FR, was selected for its footprint: 2.5" by 2.6" by 5.3", with a capacity of 3.2 Ah and a weight of 3.1 lbs.

## 2.3 WHEELS

The diameter of the wheel should be between 2" and 3" (50 mm and 75 mm) in order for the chassis to have enough clearance from the ground without the wheel size getting unwieldy or significantly raising the required torque. The axle of the motor is 5 mm with a flat portion. For the sake of space, the wheel is mounted directly to the axle as a press fit, dictating a wheel with a bore which is no larger than 5 mm. Unfortunately, 6 mm and .25" appear to be very common lower bounds for bore sizes in wheels. I was, however, able to find wheels with 3mm bores and a 50mm diameter. These wheels had to be ordered from England, but as is shown in Appendix A, the postage for shipment is not significant to the price of the robot. I tried drilling out different larger diameters into the bore and found that 3/16" allowed for a secure press fit.

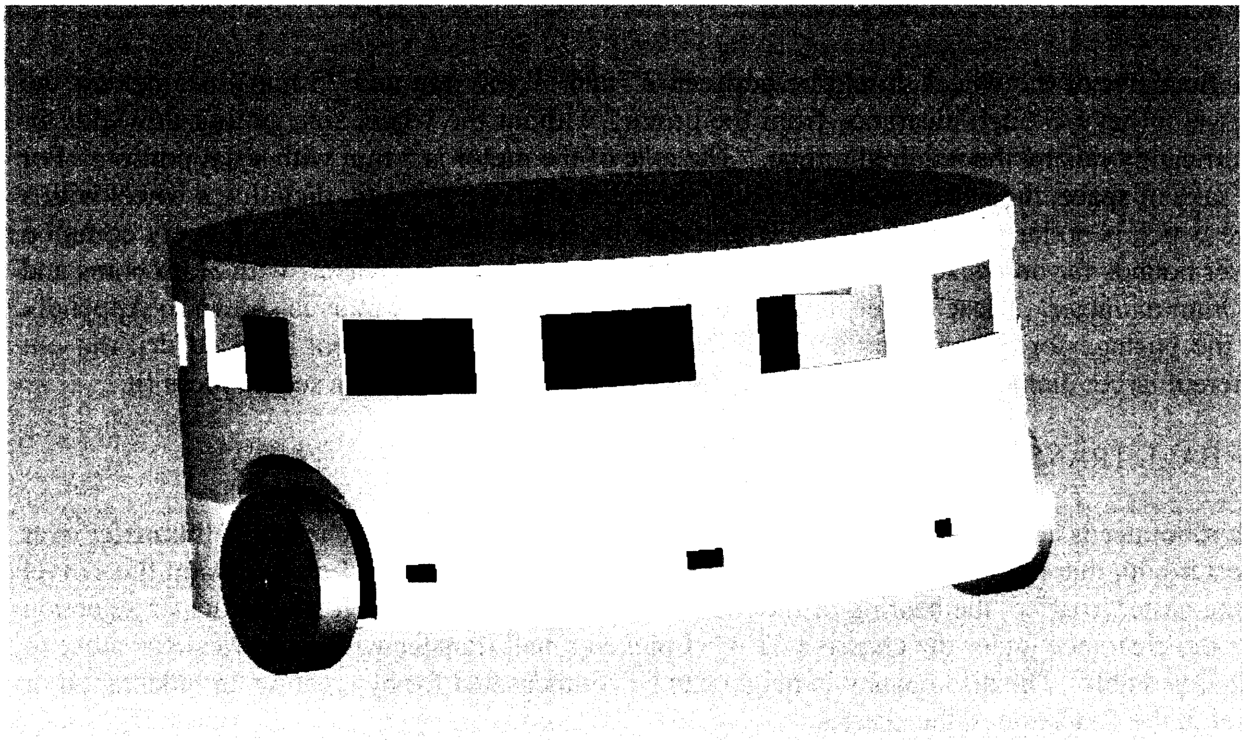
## 2.4 BALL TRANSFER

The robot needs a third point of contact with the ground for stability. I chose a ball transfer over a caster both due to the close proximity to the ground and the fact that I did not want the swivel of the caster to affect the bearing of the robot. The driving dimension for ball transfer selection was the clearance under the chassis (.33"). I picked a ball transfer with a clearance as close to that as possible. The discrepancy in height can be compensated for by creating an indentation or relief in the underside of the chassis.

## 2.5 FASTENERS

In considering fasteners, I started by thinking about how the robot would be assembled in the production line. The motor assembly has four 6 mm diameter threaded holes on the face of the gearbox from which the axle protrudes, which makes the fastener selection for that interface easy. Although the motor could be directly attached to a protrusion from the chassis, that makes for awkward assembly of the motor to the base and makes attaching the wheel difficult because of the specificity of the direction. Instead, I designed a bracket which can be attached to the motor assembly before the wheel is attached, but attached to the base after the wheel is attached. I received a quote from SLP Machine, Inc. for 500 of the brackets punched and bent out of steel sheet metal .135" thick at $3.77 apiece. Although this may be stronger than the bracket needs to be, particularly since the same part in the prototype I built is made of .125" thick aluminum, it establishes that mass producing the bracket is not prohibitively expensive. I used the same diameter bolt to attach the bracket to the chassis, though twice the length so not easily confused, so that the washers would be the same size.

The fact that the wheel is press-fit onto the shaft eliminates the need for a fastener. I designed an indentation for the battery to sit in so it needs no fastening, particularly because it's restricted vertically. The back end of the motor assembly needs to be constrained, so I left holes for a hose clamp. The last component of the mechanical system which requires a fastener is the ball transfer, which comes with a flange for #10 bolts, so that was predetermined.



a.

## 3 CHASSIS DESIGN

The chassis design is the most open ended aspect of the project. Desired design features of the chassis include interfaces for mounting every component, the ability to accommodate two different sizes of sensors around the full perimeter, and easy access to the main PCB and the battery. I considered several different methods of producing the chassis. Five hundred is an awkward production quantity since it is too many units for labor intensive processes but still few enough units to be highly affected by tooling costs. Despite its expensive set up, I selected injection molding for its versatility, particularly in snap fit connections, and precision in dimensions. I split the chassis in to three sections: a cover, a midsection and a base. This allows the user to access the main PCB, battery, and more complicated, long range sensors without disturbing the drive train and short range sensors.

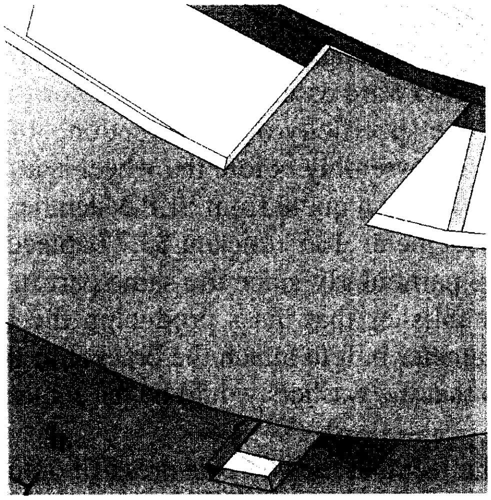


Figure 2: a. A model of the robot made in Solidworks with all interfaces idealized to points of contact. b. A close up of the integration of the sensor holes into the interfaces between the different pieces of the chassis.

This configuration is also useful from a manufacturing perspective, as the holes for the sensors can be integrated into the interface between chassis sections rather than being created by side punches and adding complexity to the mold.

The simplest method of mounting the motors is abutting the rear faces of the motors so that the shafts lie on the same axis. Since the chassis has three points of contact with the ground, I moved that axis half an inch from the center of the robot so that more of the weight of the robot would lie in the triangle formed by those three points. After adding in clearance between the motors for wire routing and partially countersinking the wheels into the base, the necessary diameter for the robot is around 9". In the prototype, the robot is actually ovoid in order to accommodate the larger encoders, so its dimensions are 9" by 9.5". I also designed a trough into the base for the motor assembly to rest in. The ball transfer is not countersunk in this prototype, but will be in production models.

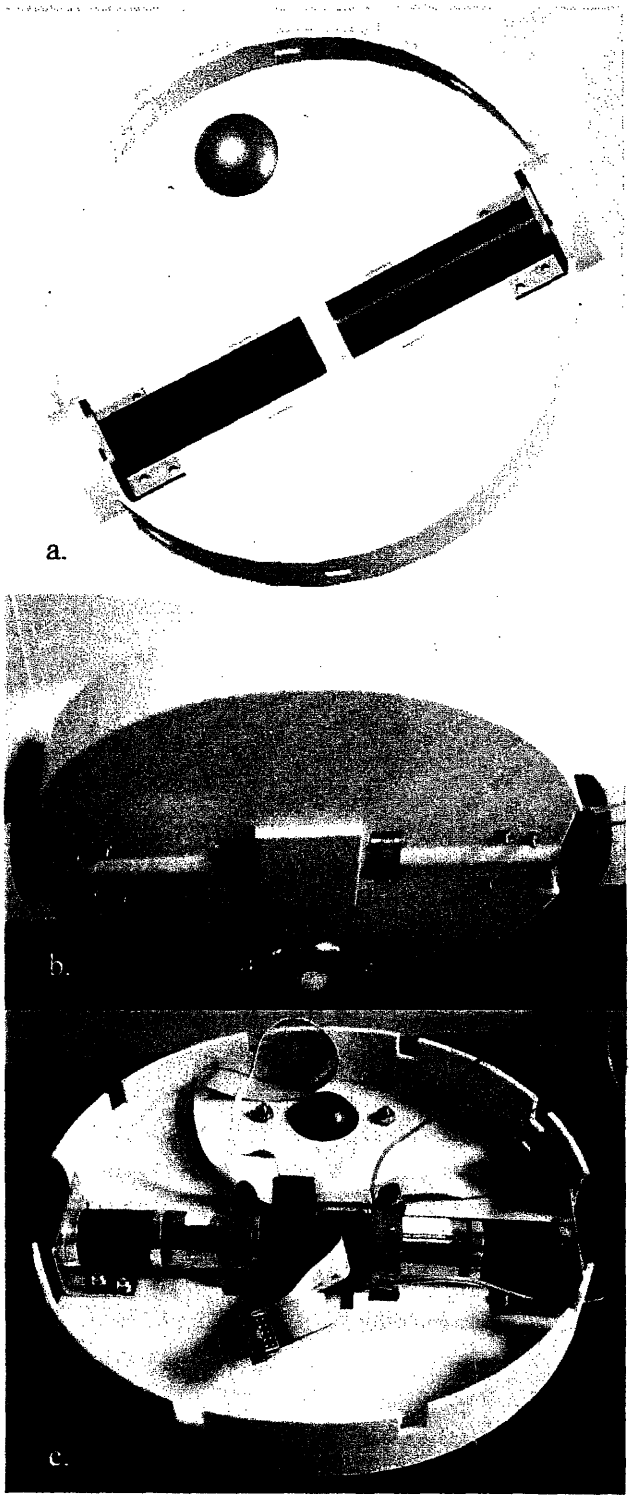


Figure 3: Here are three views of the base, one from the top, idealized in Solidworks without any fasteners, one from the bottom fully assembled, and one from the top fully assembled.

The middle layer contains mostly electronics, and therefore has fewer mechanical features. It does, however, have an indentation for the battery, which is located between the ball transfer and the motors. This centers the weight of the battery over the middle of the three points of contact, since it represents a large percentage of the machine's weight. The top section of the robot is simply a cover that interlocks with the rest of the chassis.

The holes for sensors represent a larger portion of the interface on the cover-to-middle connection as opposed to the middle-to-base connection. This should allow a similarly constructed snap fit to be stronger on the lower interface than on the top one so that one can replace the battery or alter the programming easily, without interfering with the drive system.

I received a quote from Paramount Industries for injection molding the chassis. As can be seen in Appendix A, the tooling costs are approximately $35,000, but each piece is $3 a piece in materials and labor. For quantities of 500, the chassis is $80 per robot. While this is manageable for production, I needed to find another method of producing the chassis for the prototype, so I had the parts 3-D printed on a Z Corporation machine.

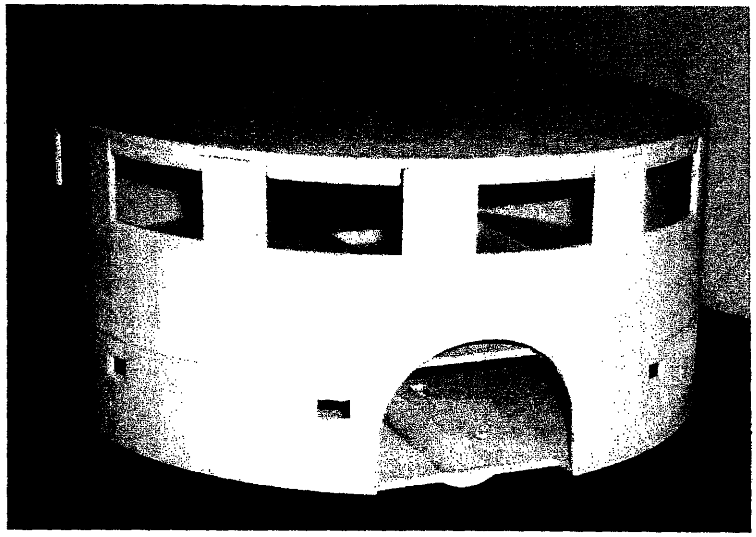


Figure 4: The 3-D printed chassis by itself.

# 4 TESTING AND DESIGN IMPROVEMENTS

## 4.1 MOTOR ASSEMBLY IMPROVEMENTS

Since no obvious mechanical issues arose during assembly and testing, I re-examined the torque requirements of the motor. I measured the current drawn under several different running conditions. The continuous current required is around .2 A, while the peak current requirement is around 1 A. Using the no load current, the maximum continuous torque, and the maximum continuous current I found the relationship between torque and current. The continuous torque related to .2 A is .002 Nm before the gearbox, and therefore .062 Nm after the gearbox. This translates to a stall torque of .409 Nm. Returning to the original calculation for required torque, I weighed the robot and found it to be around 3 kg. Adding half a kilogram to account for the electrical systems, the required torque to start from stop if the coefficient of rolling friction is .5 is .438 Nm, a comparable number to what was measured, and therefore a good estimate to go on for required stall torque. While the torque requirement turned out to be too high, the speed of the robot could stand to be increased.

From there, three routes seem viable. One is to continue with a 26 mm motor and encoder, but swap out the gearbox for one with a 19:1 ratio, another is to switch to the 22 mm motor but keep the 53:1 ratio for the gearbox, and the third is to switch to another manufacturer entirely. For the 26 mm motor option, a stall torque of at least .31 Nm and a continuous torque of at least .005 Nm are desired. With those torque requirements I can substitute the 9 V 26 mm motor for the 12 V version, which will also cut down on the size and the weight of the battery, and allows for a change from a lead acid battery to a far more cost effective battery assembly pack using C or D batteries. The unit price for these packs is between $5 and $10 at quantity on Digikey. The new combination shaves off about $50 per robot before factoring in injection molding costs.

The 22 mm motor still runs on 12 volts and therefore still needs the same battery. However, it allows for the downsizing of everything else in the design. The specifications of the motor are .002 Nm of continuous torque and a stall torque of .013 Nm, both of which are feasible. This configuration does not increase the speed, but it does nothing to decrease it either, since the speed of the motor is still above 8000 rpm, which is the maximum input to the gearbox. This new combination saves about $100 per robot in the motor assemblies.

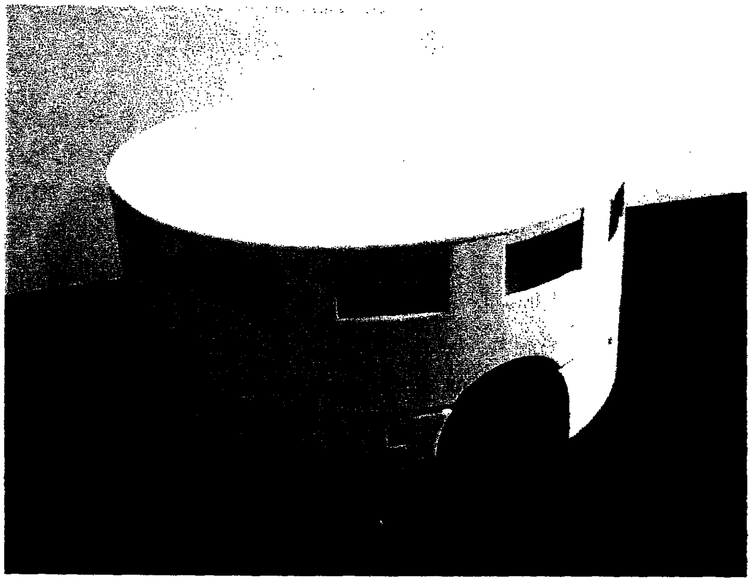


Figure 5: The fully assembled prototype.

I also found Micro-Drives, which provides motors with similar technical advantages – integrated gearbox and encoders, but appears to be slightly less high end. It is quite likely that for this application, the difference in price is more important than the difference in quality, particularly given the presence of encoders, which can compensate for discrepancies between the two motors. The particular Micro-Drives configuration I examined has the same diameter, length, nominal voltage, and continuous torque as the Maxon 22 mm motor. Its stall torque is 600 mNm to the Maxon motor's 720 mNm, but that is still within the desired range. The no load speed is 125 rpm, so less than the Maxon motors, but the Micro-Drives motor assembly purports to have a less steep drop off of speed for torque, so that while providing 62 mNm of torque, it still runs at 100 rpm. If the Micro-Drives motor really does perform that well, then it cuts $250 per robot off the price in motor assemblies, which is the large price cut the project needs.

The cost of injection molding the chassis is directly related to both the depth and the diameter of the parts. Removing a stage from the gearbox on the 26 mm motor allows for a robot with an 8" diameter rather than 9", while switching down to one of the 22 mm motors changes the necessary diameter to 7.5". The smaller battery for the 26 mm configuration changes the depth needed in the middle piece, which is currently the most expensive mold to make, while a smaller motor changes the depth needed in the bottom piece for the 22 mm configurations. It is difficult to speculate which design would lead to lower injection molding costs per part without full-fledged modeling and cost analysis of all three designs. I would, however, estimate that any of these redesigns would shave around $10 off the total price. Using that estimate, the new 26 mm assembly brings the production price down to $500, while the 22 mm Maxon Motor version brings the production price down to $450, and the Micro-Drives motor to $300.

### 4.2 OTHER SUGGESTED IMPROVEMENTS

The chassis design could be a more aesthetically pleasing from an industrial design perspective. Functionally, the main diameter of the base piece should probably be slightly smaller than that of the middle piece so that the infrared sensors have some shading from environmental effects. The cover and base could also stand to be filleted in order to look less boxy. Also, the holes fore the wheels are larger than necessary – tightening that clearance would give the robot a cleaner look.

The last aspect which will be different in the next iteration is the wheel itself. The material of the wheel is a little harder plastic than I would like, and does not have particularly good traction. I will further research model airplane wheels to see if there is an appropriate wheel I happened to miss during my original search.

## 5 CONCLUSIONS

Although the project did not achieve its pricing goal based on the components used in this prototype, it is likely that the next prototype will achieve that goal or improve significantly. If the Micro-Drives motor performs to specifications, that will halve the price of the robot, changing the suggested retail price from $1000 as quoted in Appendix A to $500, the original goal. If not, I am inclined to use the 26 mm motor, unless injection molding cost analysis uncovers a large discrepancy between the cost of manufacturing a chassis with the dimensions necessary to support a 26 mm motor assembly versus a 22 mm motor assembly. I would chose the 26 mm Maxon motor over the 22 mm one because I find the velocity difference to be more significant than the price difference – for the amount one would be paying for these versions of the robot, its speed should be limited by weight and inertia, not the motors. Even with the current motor assembly, however, the competition costs a third again as much, so the pricing is still competitive, just not as competitive as I would have liked.

## APPENDIX A: COST OF GOODS & SERVICES

The following table lists the costs of parts with their respective prices, as both single unit prices and at a quantity of 500. It also includes the tooling costs for the chassis factored in to the final price, as well as the shipping cost of the wheels, which have international shipping.

| Component | Single Unit Price | Unit Price at Quantity | Set Up Costs | Number Needed | Contribution to Product Cost |
|---|---|---|---|---|---|
| Motor | 88.50 | 48.50 | N/A | 2 | 97.00 |
| Encoder | 71.50 | 49.00 | N/A | 2 | 98.00 |
| Gear Box | 101.00 | 69.50 | N/A | 2 | 139.00 |
| Bracket | N/A | 4.00 | N/A | 2 | 8.00 |
| Chassis | N/A | 9.00 | 35,000.00 | 1 | 79.00 |
| Ball Transfer | 10.00 | 8.00 | N/A | 1 | 8.00 |
| Battery | 38.50 | 31.00 | N/A | 1 | 31.00 |
| Wheel | .60 | .40 | 118.00 | 2 | 1.00 |
| Electronics | 300.00 | 100.00 | N/A | N/A | 100.00 |
| Fasteners | 20.00 | 5.00 | N/A | N/A | 5.00 |
| **Total** | | | | | **566.00** |

Table 1: The total cost of the robot is around $600 which suggests a selling price of around $1,000. The main contributors to the cost are the motor, encoder, and gearbox, so efforts should be made to minimize their cost.

## APPENDIX B: MOTOR SPECIFICATIONS

In the following table, each of the motor configurations discussed in the paper is listed with all relevant and available data. For the prototype motor assembly, the smaller, ideal encoder is referenced rather than the one that was actually ordered.

| Motor | Servo From Educational Robot | Prototype Assembly | 26 mm Proposed Assembly | 22 mm Proposed Assembly | Micro-Drives Motor |
|---|---|---|---|---|---|
| Cost at Quantity | N/A | $167 | $154 | $114 | $45 |
| Diameter | N/A | 26 mm | 26 mm | 22 mm | 22 mm |
| Length | N/A | 94 mm | 87 mm | 73 mm | 73 mm |
| No Load Current | N/A | 57 mA | 104 mA | 46 mA | 100 mA |
| No Load Speed | 50 rpm | 150 rpm | 400 rpm | 150 rpm | 125 rpm |
| Maximum Continuous Current | N/A | 1080 mA | 1080 mA | 664 mA | 500 mA |
| Maximum Continuous Torque | N/A | 444 mNm | 106 mNm | 212 mNm | 200 mNm |
| Nominal Voltage | N/A | 12 V | 9 V | 12 V | 12 V |
| Stall Torque | 420 mNm | 2095 mNm | 532 mNm | 719 mNm | 600 mNm |

Table 2: In this side by side orientation, it is easier to weigh the pros and cons of the two proposed assemblies. The 26 mm assembly is preferable in that it has a higher top speed and a lower voltage requirement. The relative merits of the 22 mm assembly are its size, the fact that it draws less current and so will have a longer life, and higher torque values. The necessity of those higher torque capabilities, however, is not necessarily known.

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