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MULTI-PURPOSE ROBOTIC PLATFORM FOR A 100KG PAYLOAD

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ABSTRACT

The goal of the RP100 project is to design a safe, multipurpose robotic platform. There are two designs. The first is a triangular platform capable of carrying up to 25 kg. The second is an expandable, rectangular design, able to carry a payload of 100 kg. Both robots use off-the-shelf parts and interchangeable motors. The design is well documented and provided in an open source manner to the public.

INTRODUCTION

In many projects it is often necessary to have a robotic vehicle in order to achieve the initial goal. The vehicular platform may be used to find coordinates, carry a payload or simply to provide movement for measuring positioning and accelerations. It was recognized that in these scenarios it would be far more ideal to have a design for a multi-purpose vehicular platform that could be configured to the current application, instead of taking the time and effort to design one specially. In this respect the RP100 (and related projects) were born. These robotic platforms would be open source and easily modified to suit as many applications as possible. To this end a team of students set out to design interchangeable motor modules while another team's mission was to build the platforms to use them. This paper will serve to describe the design of the two robotic platforms RP100A and RP100B.

To understand the scope of the project one would have to know some basic conditions of the design. These two platforms were both for indoor use but otherwise differed in both basic shape and their respective payloads. These designs are shown in figure 1. The smaller platform, RP100A, was to be triangular, use one motor module, and carry no less than 30 kg. The RP100B robot was to be rectangular and carry 200 kg. In addition to this the rectangular platform must be expandable. This is to say they are able to use two, four or six motor modules. Both robots must be scalable so that future teams could grow and shrink the 100 kg designs into 1 kg, 10 kg, and 1000 kg versions.

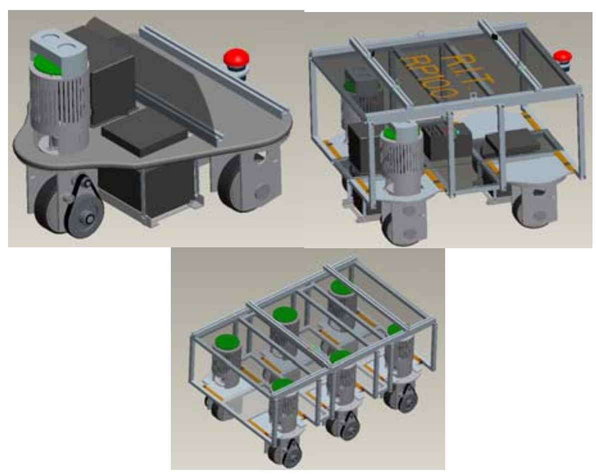

Figure 1: Rp100A (left top) and the expandable RP100B designs

DEVELOPING THE DESIGN

The design of the platforms was accomplished by breaking the project into subsystems. These subsystems were then looked at in detail in order to find the best solution. To ensure that the design for that subsystem was acceptable, certain benchmarks were set that would be achieved, later in the prototyping stage. The subsystems that were started with were derived directly from the customer needs.

Customer Needs

Through discussion with the customer and the Project Readiness Package (PRP) the scope of the project was laid out. The most important needs were determined to be:

- The robotic platforms' designs ensure safety to the users and bystanders, the facilities, the payload, and the robots themselves.
- The platforms need to be able to carry a payload anywhere in the James E. Gleason building with exception to stairs.
- The triangular, RP100A, platform carries a payload of varying shape and size, weighing 25 kg. The rectangular, RP100B, platform must carry a payload of varying shape and size, weighing 100 kg.
- Must be able to drive by remote control and autonomously navigate to programmed coordinates.
- Both designs need to use off-the-shelf components for simplicity and affordability. For hardware, metric sizes would allow for broader international uses.
- The rectangular design should be scalable in order to build smaller or larger versions as may be needed in future applications.
- Open source documentation will allow anyone to review the project and build duplicate platforms with a week's startup time.
- The design should be appealing. The design should be impressive to prospective engineering students and be an effective educational tool. This means that the final project should look professional and finished as well as be versatile enough to be of use to many people with diverse applications.

These needs have been stated in order from most important to least important. For further detail the P07205 Needs Assessment gives an even further breakdown of these needs.

Description of Subsystems

By looking at the various needs, and the hierarchy of importance, it was able to assign parts of the design that address each. This section will primarily deal with the solutions to each design issue. Past concepts can be revisited by looking at P07205's Design Process documents.

Safety

The most important need was human safety and this held in the utmost regard during the design process. Several design considerations were made solely for this purpose. Mechanically speaking, the main safety concerns were of the platform tipping over, running into something or becoming very hot.

Tipping

The worse case scenario of the robot statically tipping would be on the 5^{o} ramp and with the 100 kg payloads' C.O.G. directly above the rear of the 75 kg platform as shown in figure 2.

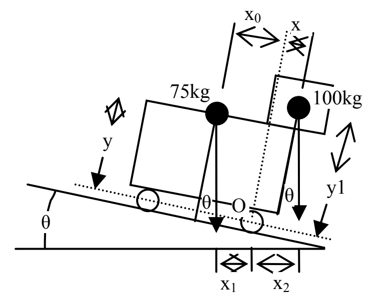

Figure 2: Worst case scenario for static tipping analysis showing approximate geometry and center of gravities.

In this case the moment created about by the payload wants to tip the robot backward. Also the moment that is created by the weight of the robot resists tipping. Both moments are calculated about the point of contact of the floor and rear wheel. If the moment produced by the payload is greater than that of the platform it will tip. The calculations can be seen below. The moment due to the platform ("the stabilizing force") is found in Eq. (6) and the moment due to the payload ("the tipping force") is calculated in Eq. (7). The conclusion of this analysis was that the platform would not tip if standing still on a standard ramp.

$$y = .342m,\ x_o = .236m \tag{1}$$
$$y_1 = .572m,\ x = .154m \tag{2}$$

$$x_1 = x_o{*}\cos(\theta) \longrightarrow x_1 = .235m \tag{3}$$
$$x_2 = (x - x{*}\cos(\theta)) + x) \longrightarrow x_2 = .154m \tag{4}$$

$$M = F * d \longrightarrow M = mg * d \tag{5}$$
$$M_p = (75kg * 9.81\tfrac{m}{s^2}) * .235m \longrightarrow M_p = 172.9Nm \tag{6}$$
$$M_{PL} = (100kg * 9.81\tfrac{m}{s^2}) * .154m \longrightarrow M_p = 151.1Nm \tag{7}$$
$$M_p > M_{PL} \therefore \longrightarrow \text{ it will not tip.} \tag{8}$$

Perhaps more important is whether or not the robot will tip during acceleration or deceleration. To determine if the robot will tip starting up a ramp from a dead stop, the acceleration needed to lift the wheels off of the ground must be found. It is known that each motor module gives 43 N-m of torque at the wheel. The maximum accelerating force for each module determined using Eq. (10).

$$T = F * r \longrightarrow F = \frac{T}{r} \longrightarrow \tag{10}$$

$$F = \frac{43Nm}{.0762m} \longrightarrow F = 564.3N$$

Because there are two modules on the rectangle the actual force provided is 1128.6 N. The force needed for a "wheelie" must be greater than this force to ensure no chance of tipping. To find the acceleration needed to tip the following equations are used.

$$\sum M_o = 0 = mg(x) - ma(y) \tag{11}$$

$$mg(x) = ma(y) \tag{12}$$

$$a = \frac{g(x)}{y} \tag{13}$$

For a center of gravity located at x = .236m and y = .473m from the driving axle it would take a sufficiently large acceleration to cause the front wheels to lift off the ground. This acceleration is shown in Eq. 14.

$$a = \frac{9.81\frac{m}{s^2}(.236m)}{.473m} \longrightarrow a = 4.89\frac{m}{s^2} \tag{14}$$

$$F = ma \longrightarrow F = 175kg(4.89\tfrac{m}{s^2}) \longrightarrow F = 855.75N \tag{15}$$

The driving force required to produce this acceleration is shown in Eq. 15. These calculations show clearly that the platform may have a chance to tip when accelerating on a level piece of terrain. Realistically the platform will probably just pull its front wheels off of the ground a bit and not actually flip up-side-down. It must also be noted that these calculations are made assuming no slippage between the wheels and the floor. The worst case scenario, however, is accelerating up a ramp. This case should be tested immediately during bench marking. If the motors are ramped up instead of simply given full current to start, the chance of tipping can be diminished. With testing it can be determined at what speed this ramping can be performed.

The motor modules have "power-off" brakes. This is to say that when the kill switch is triggered the brakes lock the wheels. This will cause the platform to tip based on the speed at which it was traveling.

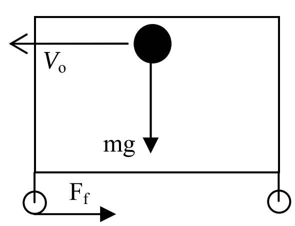

Figure 3: Model of forces on platform when the brakes are locked.

The stopping distance needed can be derived from the Work-Energy Principle. This is shown in Eq. 16.

$$W = \frac{1}{2} m * V_o^2 \tag{16}$$

Dividing work by distance will give you a force, in this case the force it takes to change the platform's momentum to zero. This idea is used to compute the needed stopping distance if the platform was traveling at 1.5 m/s and assuming a coefficient of friction of 0.7. These calculations are shown in the following equations.

$$\sum F_x = 0 = F_f - \frac{1}{2*d} m * V_o^2, \quad F_f = \mu(mg) \tag{17}$$

$$\mu(mg) = \frac{1}{2*d} m * V_o^2 \longrightarrow d = \frac{V_o^2}{2\mu g} \tag{18}$$

$$d = \frac{V_o^2}{2\mu g} \longrightarrow d = \frac{(1.5\frac{m}{s})^2}{2*.7*9.81\frac{m}{s^2}} \longrightarrow d = .164m \tag{19}$$

Using this stopping distance the deceleration can be found as follows:

$$V^2 = V_o^2 + 2a(d - d_o) \tag{20}$$

$$a = \frac{V^2 - V_o^2}{2(d - d_o)} \tag{21}$$

In this case the final velocity will be zero as well as the initial distance, realizing this will yield a deceleration:

$$a = \frac{V_o^2}{2(d)} \tag{22}$$

Using the stopping distance calculated above with the same initial velocity it was found that the deceleration was:

$$a = \frac{(1.5\frac{m}{s})^2}{2(.164m)} \longrightarrow a = 6.86\frac{m}{s^2} \tag{23}$$

Looking first at tipping without a payload the C.O.G. is located at x = .172m and y = .230m. These measurements are taken from the point of contact between the driving wheel and the floor. The mass of the platform without payload is 75kg. The deceleration previously calculated ($6.86 m/s^2$) will be used to determine whether or not tipping will occur.

$$\sum M_o = 0 = ma(y) - mg(x) \tag{24}$$

$$ma(y) = mg(x) \longrightarrow a(y) = g(x) \tag{25}$$

$$(\frac{y}{x}) = \frac{g}{a} \tag{26}$$

$$(\frac{y}{x}) = \frac{9.81\frac{m}{s^2}}{6.86\frac{m}{s^2}} \longrightarrow (\frac{y}{x}) = 1.43 \quad (27)$$

Given this particular deceleration the ratio of y/x for the COG cannot exceed a 1.43 otherwise tipping will occur. Therefore the given ratio of .230m/.172m = 1.34 (without a payload) will not tip. This braking action holds the most concern and therefore will determine the restrictions of combined COG. A plot of the range of acceptable COG's is shown in Fig. 2.

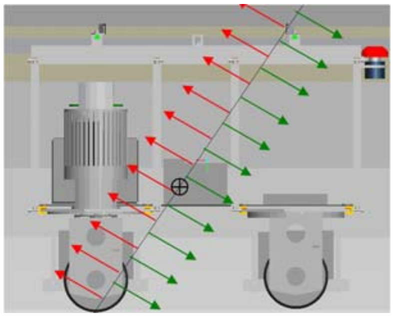

Figure 4: To ensure that the platform does not tip when the brakes locking, the COG should not enter the zone signified by the red arrows.

A common factor to all these tipping calculations is the platform's center of gravity (COG). The robot has been designed to lower its COG by hanging the large batteries under the frame. The two batteries weigh a cumulative 40 pounds which is about as much as the frame. It is the weight and height of the motors that raise the COG so much.

Collision

Even limiting the maximum speed of the platform to 1.5 m/s (4.5 ft/s) it takes 0.164 m (6.5 inches) to stop. This was calculated in Eq. (19). A fully loaded platform weighs 175 kg which certainly could pose danger to people, the robot and the facilities if not addressed. To help this danger, safety bumpers were affixed to the entire perimeter of the platform. By adding a kill switch the user or bystanders can stop the robot in case of an emergency. Both the bumpers and the kill switch can be seen in Fig. 5. These bumpers not only give protection in the form of displacing collision energy by deformation but they also act as a trigger for the kill switch. Embedded into the bumpers is a contact strip that allows this.

The steel frame of the rectangular RP100B offers a lot of protection for the robot. Using steel was a cheap option that offered more robustness than the alternatives. For the RP100A, an ultra high molecular weight polyethylene was used. This frame is shown in Fig. 6.Though an inch thick piece was needed for the robot, it is surprisingly tough.

Figure 5: A picture of the actual RP100B showing the steel frame and safety bumpers. Also shown are the headlights (blue). While being mainly for utility they also signal bystanders.

More than able to carry the 25 kg payload specified, it can easily survive a high impact collision. This has been proven through testing in which the platform only suffered minor dents where it was impacted. It may be noted here that the type of polyethylene used is extremely non-absorbent. This is helpful for stain resistance and easy cleaning.

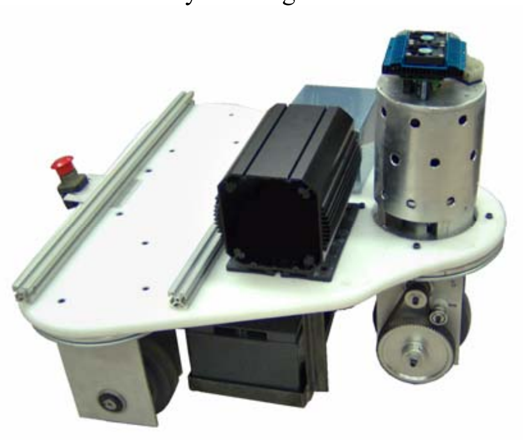

Figure 6: A picture of the actual RP100A showing the plastic frame.

Overheating

To avoid the platform or its components getting dangerously hot, certain design considerations were made. Among these is the open design. Both platforms were designed to have a lot of airflow over the batteries and the motors because these are the main heat producing pieces of equipment. Heat shields were also installed on the motors along with the heat sinks and fans located on top. These are visible in both Fig.'s 5 and 6.

Navigating the Facilities

One of the most basic needs was for the platforms to be able to be used in the James E. Gleason building. The concerns here were mainly that the robots were small enough to fit in elevators and doors and also able to climb any of the ramps found in the building. Standard interior doors are 34 inches wide so the robots were designed to fit this dimension. RP100A and RP100B both fit easily. The package dimensions are given in Fig's 7 and 8.

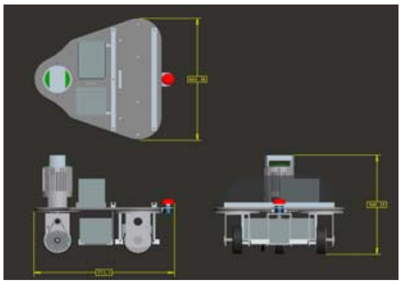

Figure 7: Package dimensions of RP100A

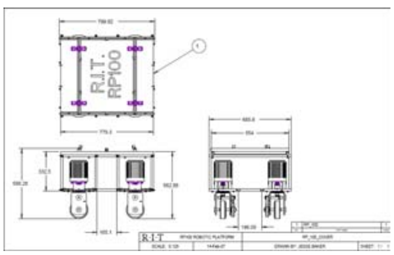

Figure 8: Package dimensions of RP100B

To climb the ramps an analysis was carried out to determine if a fully loaded platform could climb a ramp of five degrees incline. With this ramp angle an acceleration of .9m/s^2, and a total mass of 175kg the required torque is as follows:

$$\sum F_x = 0 = F_T - ma - (mg)\sin(\theta) \quad (28)$$

$$F_T = ma + (mg)\sin(\theta) \quad (29)$$

$$F_T = 175kg(.9\tfrac{m}{s^2}) + (175kg * 9.81\tfrac{m}{s^2})\sin(5) \quad (30)$$

$$F_T = 307.13N \quad (31)$$

$$T = F_T * r \quad (32)$$

$$T = 307.13N * .0762m \quad (33)$$

$$T = 23.4N - m \quad (34)$$

Each motor module gives 43 N-m. It can be concluded from this that both platforms can climb a five degree slope with no problem and will be up to full speed in less than two seconds.

Accommodating the Payload

To attach and carry the payload, two things were of most concern. First of all, the platforms needed to be structurally able to carry their respective loads. Secondly, the payload mounts had to be versatile enough to fit a payload of varying size and shape.

Payload Weight

To determine if the structures that were designed were strong enough to hold the weight needed stress simulations were run using ANSYS. The motor modules are known to hold 600 pounds when mounted to the turntables. The components that needed to be checked were determined to be the frame and the payload mounting rails. These results of the analyses are shown below.

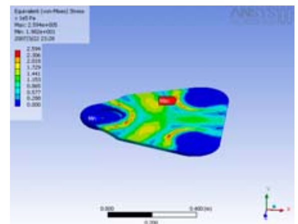

Figure 9: Equivalent stress analysis of the RP100A plastic frame under full load.

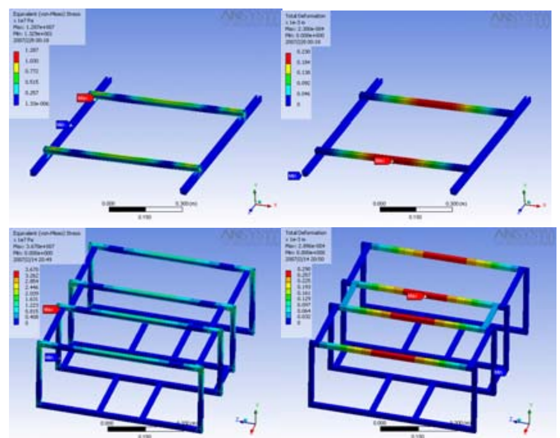

Figure 10: Left column shows equivalent stress analysis of the RP100B's payload rails and steel frame under full load. Right column shows deformation of these two components under this loading.

The ultimate strength for the steel used for the frame is around 385 MPa. The ultimate strength for the aluminum used to make the mounting flanges and payload rails is 228 Mpa. Lastly the ultimate strength for the polyethylene that was used in the RP100A's frame is 40 MPa. Every structure proved to be stron enough in analysis. The lowest factor of safety here was 10. The motor modules will fail before the platform or any of there components under uniform loading.

Payload Attachment

To fit payloads of varying sizes and shapes a sliding rail system using t-nuts was developed. This gave us an analog positioning system that could be easily tailored to the application at hand. It also gives the option of simply adding more rails if needed for a larger payload. By adding more t-nuts it is possible to add accessories such as tie-downs, clamps, grips etc. These are shown in Fig. 11.

Two different covers that can be secured under the rails are used for their suitable functions. With the Plexiglas cover the platform is only meant to have the payload secured onto the rails but it allows one to look into the "guts" of the robot more easily. Conversely there is a diamond plate cover that can be used instead. This allows the user to set the payload on the flat plate and secure the cargo with the rails.

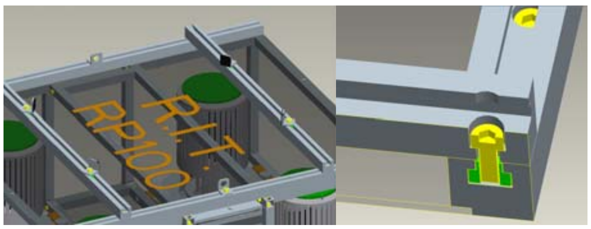

Figure 11: Picture of the rail system with grips and tie-down accessories. The left picture shows how t-nut fixes the rail in position.

Navigation Software

In order to control the robotic platform via tethered remote and autonomously navigate to programmed coordinates, the software and communication systems must consist of the following software/hardware subsystem interfaces: 1) decoders, 2) user interface to command converter, 3) main controller, 4) PWM signal generator. To implement such system, VHSIC Hardware Description Language (VHDL) language was chosen to interface with the motor modules and its various components. Altera UP2 development board was used. This is shown in Fig. 12.

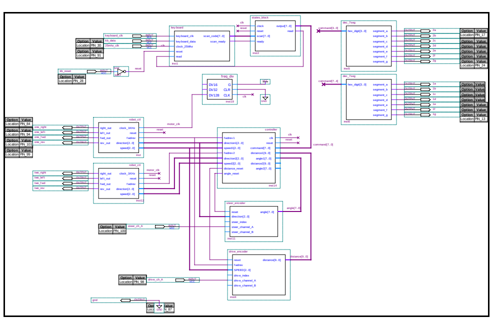

Figure 12: Block diagram of program

User Interface to command subsystem

The intended original user interface communication protocol of the project track was CAN. The design of the motor module CAN transceiver was not functional. A contingency plan of using a keyboard as the user interface was implemented. A communication "keyboard" block was design to interface with a keyboard. The key presses are then translated into commands that can be interpreted by the software algorism.

Decoders

The decoder block decodes the drive encoders and steering encoders into logic vectors that represent the angle and distance the motor. This is then sent to the controller block as feedback for autonomous navigation.

Controller subsystem

The entire controller subsystem is design as a finite state machine (FSM). Each command corresponds to a state where the software is designated to perform certain tasks such as "move_foward" and "turn_right". The feedbacks from the decoders will allow the controller to observe the angle of the motor modules and distance traveled by the motor modules. The controller subsystem has two arrays which stored coordinates for autonomous navigation. When the command to autonomously navigate is sent, the state of the FSM jumps to 'auto navigation'. Using the decoders, current (x,y) position and next (x,y) coordinates, a control algorism is set up to control the movement and turning of the motor to autonomous navigate to the next (x,y) coordinates.

PWM Generator

This block interprets the control signals outputted by the controller subsystem to generated PWM outputs to the drive motor and steering motor h-bridges.

Common Hardware

All hardware components, electrical and mechanical, that have been used in these designs are commonly used off-the-shelf parts. It has been a goal and subsequently verified that there are at least two suppliers for each piece of hardware that has been used. P07205's Bill of Materials (BOM) has detailed vendor information for future reference.

All components in the developed wiring scheme for the robotic platform, including all connectors, are OTS and are readily available to purchase from designated electrical component distributors such as Digikey and Mouser, as well as from the developer websites such as Molex. The 6 AWG and 10-16AWG wires are available through the producer themselves, or through distributor companies such as Digikey. The development board, ALTERA UP2, is also readily available from ALTERA itself and is also available through electrical engineering departments. The constructed power board, which is able to regulate power distribution between the platforms multiple external module components, is also fully built using OTS components with the exception of the customized printed circuit board (PCB). The passive components, FETs, and IC's are also available from any major electrical component distributor.

Scalability

The mechanical aspect of scaling up or down in size is strictly a matter of determining the materials and size one should use. The general designs can easily be recycled for the RP1 or RP1000 project. With respect to wiring design and connections development, scaling from a 10 kg robotic platform or 100 kg robotic platform to a 1kg or 1000 kg platform respectively would not be a major issue. One thing which would have to be taken into consideration would the difference in lengths for cabling depending on size of the motor modules, which would put a constraint on the size of the overall platform. Another aspect which has to be considered would be how much current the batteries which supply power to the motor modules would draw. Depending on the current draw, research has to be conducted to determine the wire gauge which would yield safe usage in providing power to the robotic platform.

The current power design being implemented in the RP100 robotic platform is one of two original power board designs. Due to an easier method to scale the RP10 power board design, the RP100 platform currently utilizes the RP10 design. Judging from the similarities in electronic power needs between the RP10 and RP100 robotic platforms, it is certain safe to assume that the electronic power requirements of RP1K and RP1000K would also be similar except for the increase in voltage and current draws. In order to account for the increase in required voltage and current, the regulation resistor for the power board in both the 5V and 12V regulation would have to be adjusted to reflect the new required voltages. The total amount of change would be a total of 1 resistor for slight changes, or a maximum change of 2 resistors for major adjustments (the resistors to be modified would be the regulation resistor, as labeled in the TPS5420 and LM3478 datasheets. This is a vast improvement from requiring a complete and total power board component change to reflect the required changes for a scaled up model in the RP1K and RP1000K.

Open Source

The details of the design, including the drawing package and the electrical schematics, are all available on the RP100 Edge website. Permission to gain access to these files is granted by contacting the Mechanical Engineering Department of the Rochester Institute of Technology. The materials are available so that it will take approximately one week's time to become familiar with the designs and start building the assemblies.

Appealing Design

The aesthetic qualities of either design rely heavily on the craftsmanship with which it was built. To improve the appearance of the platform the frames or components can be painted. Also graphics or such accessories such as lights could certainly be added. The designs don't currently have any of these amenities, per se, but could definitely be great additions for the future.

The designs do currently have some appeal when versatility is needed. For example, RP100B's bolt-together design allows for more motors or a larger payload mounting surface to be easily added. Conversely the relatively smaller RP100A's design may be a less complicated and relatively smaller solution for the application at hand.

Power Board

To make the platforms more useful, a power board has been designed to allow for multiple onboard, auxiliary, DC power outlets for tools, sensors etc as well as distributing power to the platforms subsystems.

Two initial designs for a power board were developed by the RP100 and RP10 teams. Due to scalability requirements, the RP10 power designed proved to be the more useful power board of the RP100 and RP10 teams. The Power Board is currently designed to provide power to the Motor Control Module, the DAQ, a SBC, and external accessories, as seen in Table 1.

Subsystem	Voltage *(V)*	Current *(A)*	Total Power *(W)*	Regulated Source Needed?
Motor Control	12	1.0	12	No
Small Board Computer	12	0.5	6	Yes
	5	1.0	5	Yes
DAQ	12	1.5	18	No
Accessories	5	2.0	10	Yes
	12	2.0	24	Yes

Table 1: Platform Power Distribution RP100, two motor module configuration

Due to some setbacks to the current motor controller design, the power board will have to be primarily used to distribute power to the ALTERA Development Board being used as the controller. The Power Board consists of 4 available outputs, rated at 2 12V 2A outputs and 2 5V 2A outputs. In order to provide sources requiring a regulated 5V input, a Buck DC-DC regulator has been utilized. The Buck regulator will take 12V in from the battery and output a regulated 5V. Based on work done by team P07202, a TPS5420 DC-DC regulator was chosen for this application. This regulator has many integrated features, including built-in power MOSFETS, and therefore requires only an external power inductor and a few passive components to operate. The application circuit for this part is shown in Fig. 13.

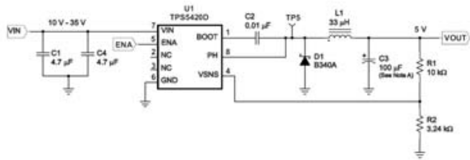

Figure 13: TPS5420 Application Circuit

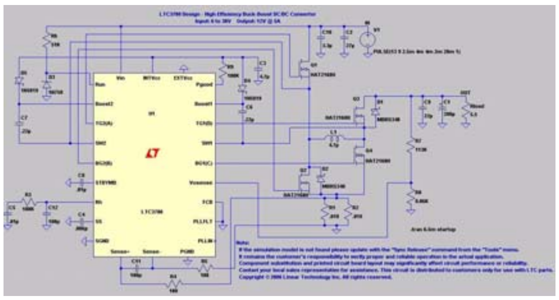

Figure 14: LTC3780 Application **Circuit**

In order to provide sources requiring a regulated 12V input, the LTC3780 IC (Fig. 14) which is able to take 12Vin and output 12V has been adopted. The LTC3780 automatically switches between Buck, Boost, or Buck-Boost modes to provide a regulated output at, below, or above the battery voltage level at efficiencies up to 98%. The LTC3780 is able to provide a regulated 12V output regardless of a drop in input voltage from 13V to 9V. V_{OUT} initially rises to slightly higher then 12V during the device's startup period (known as soft start), but after the start up period, settles at required output of 12V. The device maintains a regulated output voltage within +/-1% of 12V. The output voltage ripple during simulation was found to be to be ~10mV, suggesting that an output capacitor of 390uF with an ESR of ~50mΩ would be sufficient for proper regulator operation. The ripple current through the inductor was measured to be ~1.2A with a maximum current level of ~3A.

As a contingency plan, due to the complexity of the 12V regulator circuitry and the potential of manufacturing problems of the PCB, in order to continue to provide the required 7V-12V input to the ALTERA development board despite problems with the 12V regulation, the resistors labeled as R2 in the 5V regulation circuitry may be changed in order to "buck" the 12V battery output voltage into the range of 7V-12V for the development board. Based upon the circuitry of the 5V regulation to the 12V regulation, there is a higher chance of success for the 5V regulation circuitry to operate as intended. Resistor changes and circuitry modification to the 5V regulation does not pose any significant hazards to the success of the RP100 team.

CONCLUSION AND SUGGESTIONS

This project has succeeded in developing a robust, heavy duty, multipurpose robotic platform. By keeping two main ideals throughout the design process the platforms are both versatile and safe. Though the range of uses is too large to list, these robots certainly will be of great use to other projects that don't have the time or manpower to design a specialized machine for their specific purpose. Instead the family of RP designs can be tailored to the explicit use that is at hand.

The motor controller that was to be used was, unfortunately, not able to be finished in time for this project. In the future, when this is incorporated, there will be several more benefits to the overall platform design. Using the controller instead of the Altera board will free the auxiliary power outputs of the power distribution board. The controller would also be a much more reliable source of communication between the user and the platform, allowing a real-time interface. It would certainly be helpful for many applications to have control of the robot wirelessly. Currently, the design and programming is intended for a tethered connection between the platform and a keyboard. A handier controller may also be incorporated, i.e. a joystick.

The mounting faces on the motors that are used to attach the motor modules to the frame would be much easier to mount to if it was square instead of round. This would allow for the mounting flange in the current design to essentially be part of the motor module.

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