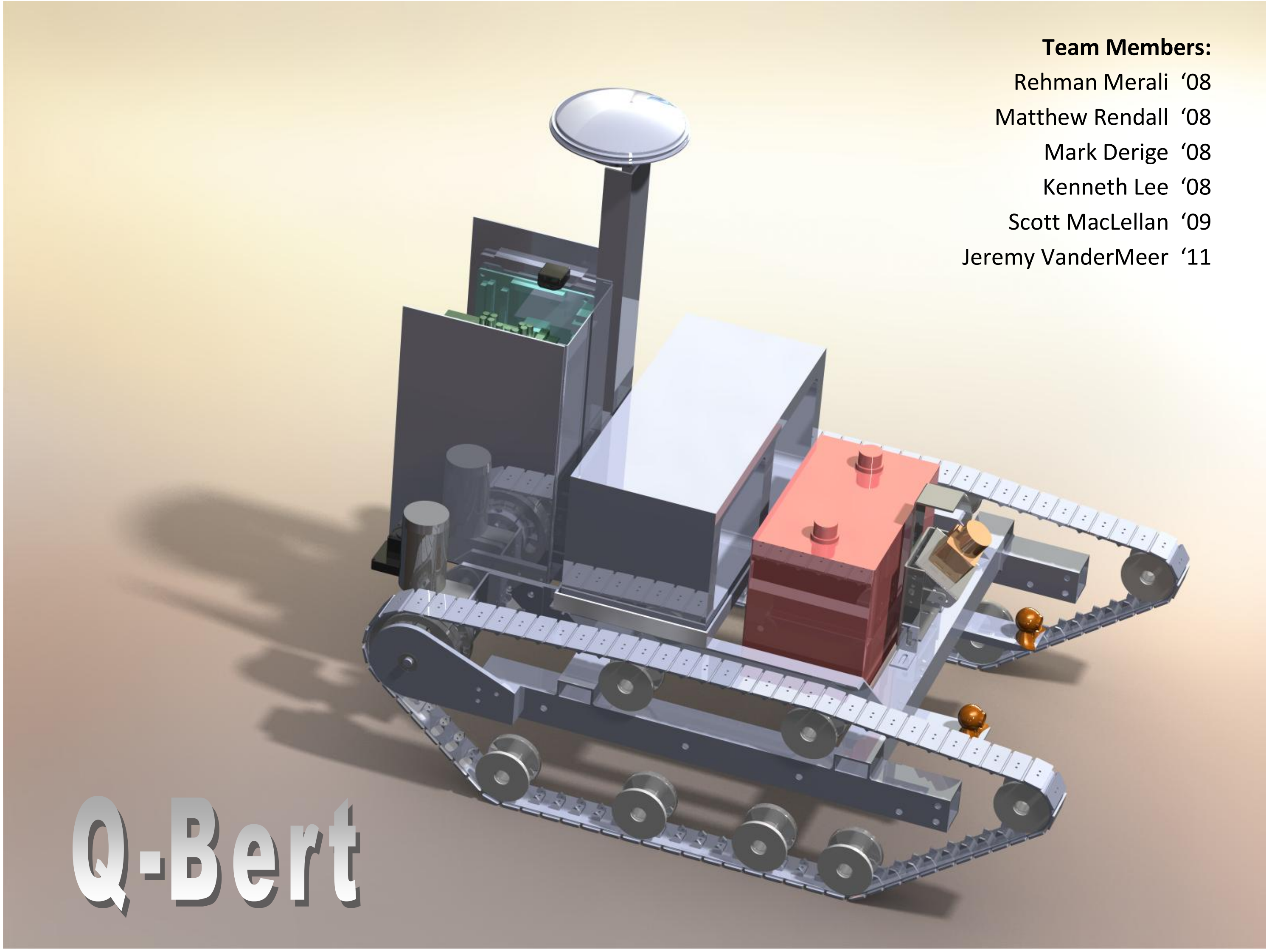
UNIVERSITY OF
Waterloo

UNIVERSITY OF WATERLOO
ROBOTICS TEAM



Q-Bert

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IGVC
Intelligent Ground Vehicle Competition

I, Dr. William Melek, assistant professor in the Department of Mechanical and Mechatronics Engineering at the University of Waterloo, certify that the engineering design presented in this document for the Q-Bert robot by the current student team has been significant and equivalent to what might be awarded credit in a senior design course.

Prof. William Melek <wmelek@mecheng1.uwaterloo.ca>

Date

Introduction

The University of Waterloo Robotics Team (UWRT) presents its first entry in the Intelligent Ground Vehicle Competition (IGVC). The robot is named Q-Bert after the QNX real-time operating system at its core. The robot has been fully designed and constructed by undergraduate members of the team. Q-Bert is built for rugged terrain with an emphasis on safe autonomous operation. Every component of the robot is novel, as UWRT is entering IGVC for the first time in 2008. This report further describes these novelties.

Mechanical Design

Frame, Battery, and Cinder Block

The vehicle frame, shown in Figure 1, is made of welded aluminum square channel for rigidity to accommodate the weight of the battery, cinder block, and other components. The placement of the battery and cinder block are shown in Figure 2. The Trojan 12-volt, 24-cell battery weighs 50 pounds. The battery is mounted in a dedicated aluminum holder, located forward of the midplane of the vehicle and centered laterally to ensure stability and longer tread life of the vehicle. It is placed near the front of the vehicle to fit the cinder block immediately behind and the electronics in the rear, maintaining a center of gravity near the geometric center of the vehicle. The mounting brackets are simple aluminum sheet and aluminum extrusions, and are fastened to the frame using bolts or screws. There are several custom-machined precision components made on the lathe and milling machine, including the bearing mounts and the shaft extender for more reliable and frictionless power transmission.

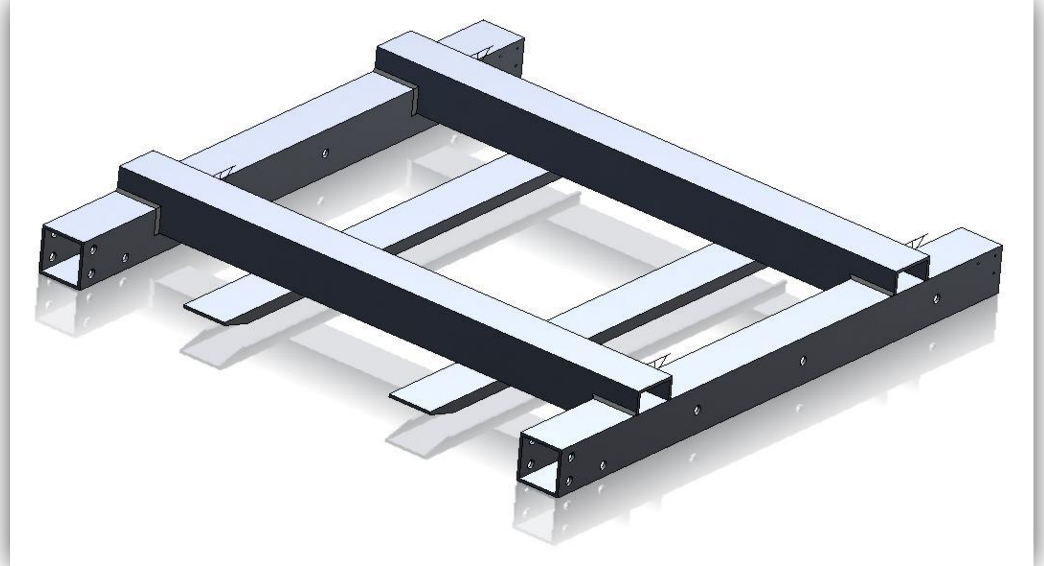

Figure 1: Welded Frame

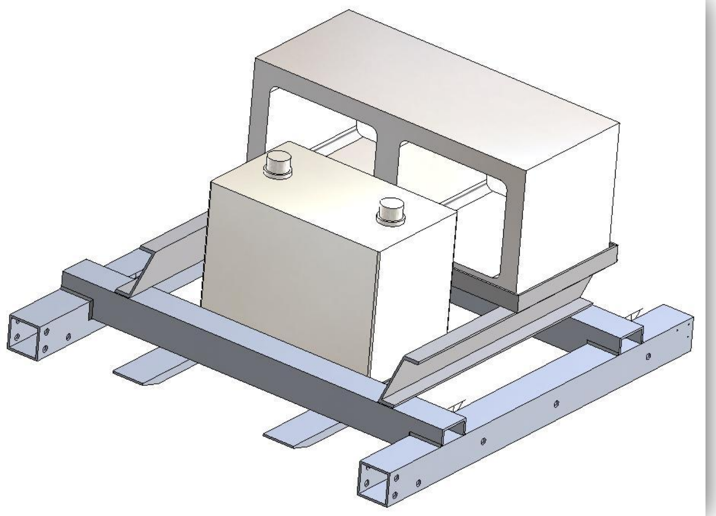

Figure 2: Welded Frame showing Battery and Payload

Tank Treads and Drivewheel

Q-Bert is unique in that it uses custom-made tank treads as opposed to wheels. This decision was made to ensure Q-Bert can handle rugged terrain like the sandpit in the competition. The major drawback to treads as opposed to wheels is speed. However, Q-Bert is still designed to reach the 5-mph maximum speed for IGVC-2008. The tank treads are custom fabricated using aluminum plates with glued sandpaper for enhanced traction. The teeth for the drivewheel are individually cut and bent to shape, then riveted to a flat nylon belt before being glued together; illustrated in Figure 4. This custom tread is mounted on a multi-spring suspension system and will conform to the terrain to allow travel over rough terrain and obstacles, and can even advance along steps of a staircase. The drivewheel is a four-disc polyethylene assembly with steel plate inserts. As shown in Figure 3, these are arranged in a fan array and act as gear teeth to advance the tread. The full assembly is illustrated in Figure 5.

Figure 3: Drivewheel Assembly

Figure 4: Tread, Close-Up

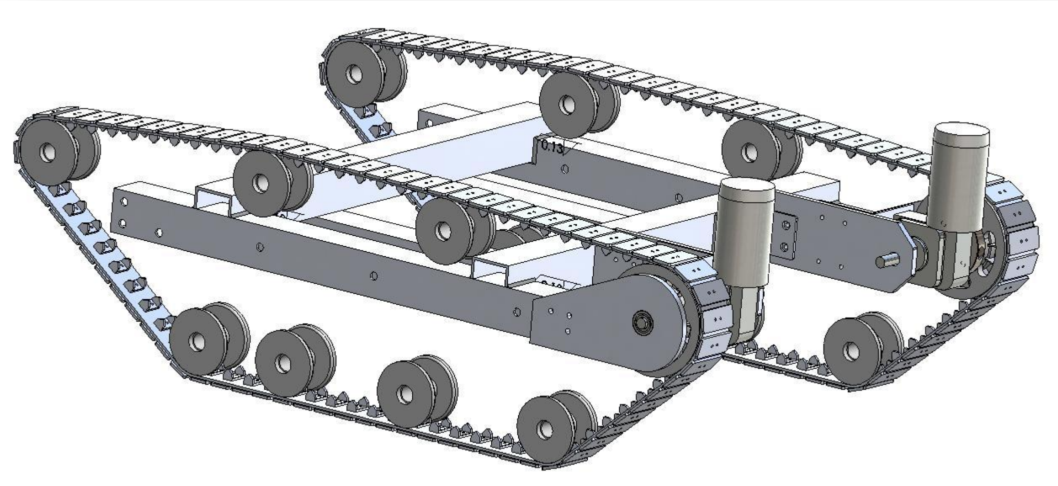

Figure 5: Tread and Drivewheel Assembly

Motors and Encoders

The NPC 2212 motors chosen are reversible and have an integrated gearbox for improved torque transmission. These motors have an 80A stall current, and therefore the IFI Victor 885 motor controllers were chosen because they can provide 120A continuously. The motors are mounted in the rear and connected to the drivewheel via a shaft extender, and a locking collar is used to engage the drivewheel to the drive shaft. The Grayhill optical encoders are mounted on the open ends of the motor shafts on the inner side of the vehicle for motor speed feedback control. The full assembly is shown below in Figure 6.

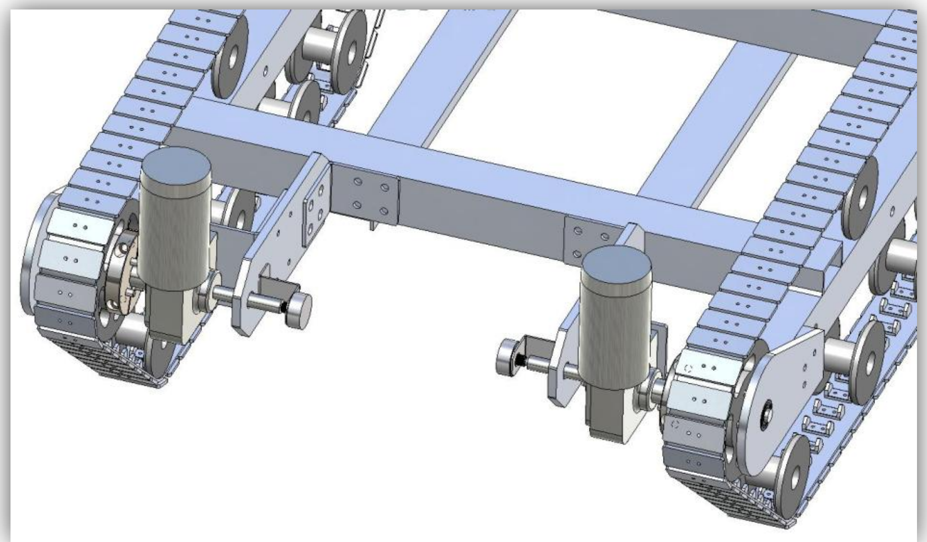

Figure 6: Motors, Mounts, and Encoders

Navigation Sensors and Illumination

The MotionNode IMU is mounted in the electronics compartment and fastened securely to minimize the effect of vibrations. The GPS unit consists of a NovAtel receiver and antenna. The receiver is placed at the bottom of the electronics compartment while the antenna is mounted on the highest point of the vehicle, beside the emergency stop, for improved reception; shown in Figure 7. The Hokuyo URG-04LX scanning laser rangefinder is mounted on an adjustable sensor tower with a pivoting platform to angle the LIDAR accurately. Two Logitech web cameras are mounted in the front on either side of the LIDAR to provide a clear view for the object recognition software, as seen in Figure 8. Two halogen headlights are mounted at the front of the vehicle to provide adequate illumination for the cameras.

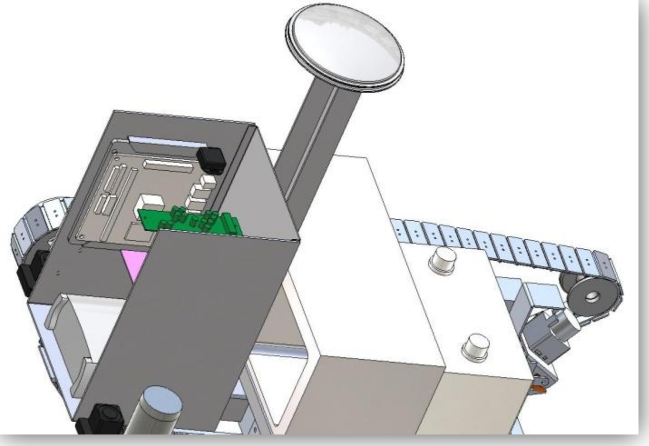

Figure 7: GPS sensor tower (top), LIDAR (bottom right), and electronics housing

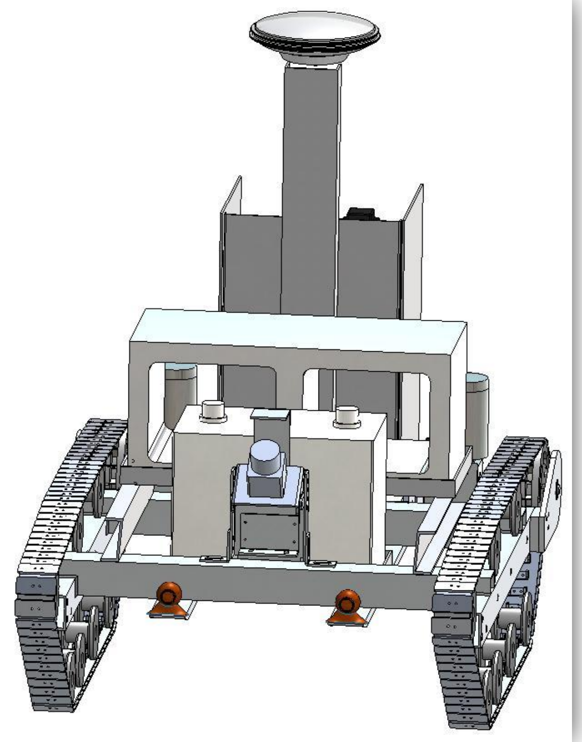

Figure 8: Robot front view with cameras and LIDAR unit (lower front), GPS antenna (top)

Emergency Stops

The emergency stop (E-stop) is a Honeywell push-pull switch and is located 3 feet above the ground beside the GPS antenna in an easily-accessible location and height. The All Electronics Corp. 12-volt wireless E-stop receiver is mounted in the electronics compartment.

Computer and Electronics Console

Figure 9 illustrate the electronics compartment, which consists of an aluminum chassis in the rear of the vehicle and a number of rails for mounting the PCBs. The VIA EPIA Mini-ITX, PWR-M2-ATX power supply board, motor speed controllers, custom PWM board, and custom power distribution board are each mounted on separate polycarbonate plates and can be slotted into the chassis for simple installation and removal. The various receivers and sensors are mounted in the chassis. The entire chassis can be detached from its sliding guides and provides access to the motor assembly as necessary. Wiring harnesses are fed through the aluminum extruded channel frame to protect the wires.

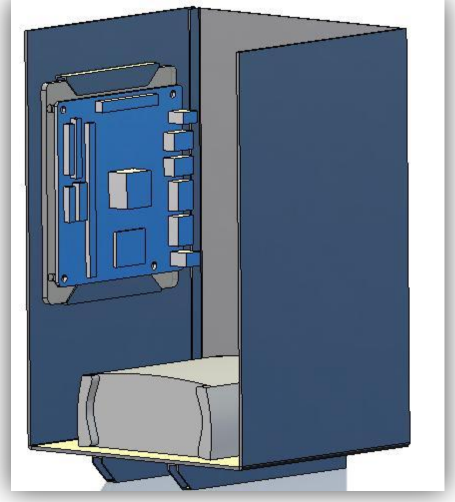

Figure 9: Electronics housing with VIA EPIA Mini-ITX motherboard and GPS receiver

Sensor Suite

Positioning Sensors

Encoders

Since the NPC motors chosen for this robot have a shaft on both sides, the robot was not restricted to through-hole encoders. Therefore to save cost and calibration, sealed shaft encoders were chosen and a custom coupling was built to attach the encoders to the motors. The encoders chosen are the Greyhill 63R encoders that have two channels at 128 pulses per revolution. Therefore, using quadrature decoding each motor's direction and rotation is known with $\frac{360^\circ}{(128)(4)} = 0.703^\circ$ resolution. Given the drive wheel diameter of 5" and a track depth of approximately ¼", the encoders are able to detect the robots change in position with $\frac{(\pi)\left(5"+\frac{1}{4}"\right)(0.703^\circ)}{360^\circ} = 0.032"$ resolution.

Differential GPS

Differential GPS (dGPS) is the only sensor that equates the robot's position to the global reference frame. However, dGPS is the least accurate of all the positioning sensors. Therefore, the other sensors are used to augment the dGPS readings. The UW Robotics Team purchased a NovAtel OEMV-3 with its associated antennas. The package purchased is meant to be used as a pair – one stationary and one mobile. However, given the IGVC rules that off-board sensors are not permitted, Q-Bert only uses half of the package and can therefore only achieve 1.5m accuracy; hence additional sensors are required to augment its localization accuracy.

Inertial Measurement Unit

When performing dead-reckoning with mobile robots, traditionally encoder data is fused with inertial data reported from an Inertial Measurement Unit (IMU). Given the limited budget of a student team, then MotionNode IMU was chosen for Q-Bert. The MotionNode reports the robots angle about all three axes within 0.5° to 2° RMS error. Within the context of the IGVC competition, the angle about the roll axis is used to determine if one of the robot's tracks has sunken into a pothole. The robot's pitch is used to determine whether the robot is climbing or descending an incline – the PWM signal to the motors is expected to change accordingly. Most importantly, the IMU reports the robot's yaw angle which is fused with dGPS and encoder data to determine the robot's heading.

Obstacle Detection Sensors

Laser Range Finder

The Hokuyo URG-04LX is an excellent sensor for mobile robotics. Although not as powerful as the industrial Sick LIDARs, the Hokuyo sensor is less than half the price. Furthermore the Hokuyo sensor has a 240° view – it can therefore detect obstacles in its peripheral vision. The maximum range of the LIDAR is 4 meters and it measures with 1 centimeter accuracy. The laser range finder is the primary sensor for obstacle avoidance; it is used detect any and all obstacles with height.

Webcams

Q-Bert uses two Logitech QuickCam Express webcams. One webcam is mounted on either side of the robot and each is responsible for detecting the line on its respective side of the robot. The only other obstacle that the laser range finder cannot detect is potholes. Therefore if time permits, the webcams will also be used to detect potholes; however this has not been implemented as of yet. For IGVC-2008, a 5-feet penalty is given for running over potholes; therefore avoiding potholes was not given priority.

Electrical Design

Once the computers and sensors were finalized, the power and communication requirements for all components were assessed. This assessment can be seen in Figure 10. The robot's motors were chosen to supply the necessary speed and torque from a 12V source. Also, the Mini-ITX computer was chosen because it can be run from a 12V car battery. However a lead-acid car battery is meant to supply a large current for a short time to start an engine. Car batteries are not meant to be drained very low – as is the case for this robot. Therefore a deep-cycle lead-acid battery was chosen. A sealed lead-acid battery would have provided additional convenience, however no sealed lead-acid battery can provide the equivalent AH as the Trojan SCS150 for nearly the same size and weight. The Trojan SCS150 is heavy at 50-lbs, and approximately the size of a large car battery, however its 20-hour Amp-Hour (AH) rate is 100.

Emergency Stop

For safety, a large red emergency stop (E-stop) was mounted on top of the robot and a wireless E-stop was also implemented. The wireless E-stop is simply a remote controlled (RC) relay which can operate from 120'. The motors can draw a maximum of 35A (fuse protected) each. Therefore the E-stop must be able to supply 70A during operation. Neither of the chosen E-stops can supply a current this large, therefore the two E-stops were placed in series and control a 12V relay. If either E-stop is pressed, the relay unlatches and power to the motors is cut. Note that it is only necessary to cut power to the robot's outputs – the motors in this case.

Noise Suppression

Given the high current and constant switching of the PWM signals and the electromagnets in the DC motors, there is a great deal of noise generated on all electrical lines. Therefore the motors are electrically isolated from the remaining electronics. A 12V DC-DC isolator is used to isolate the two 12V lines. However, the 5V servo-style PWM signal from the SAM-7 microcontroller to the Victor-885 motor controllers is also optically isolated to ensure the ground wires are kept separate for the two circuits. To further reduce noise to sensitive electronics, several low-pass filters have been added to the circuitry.

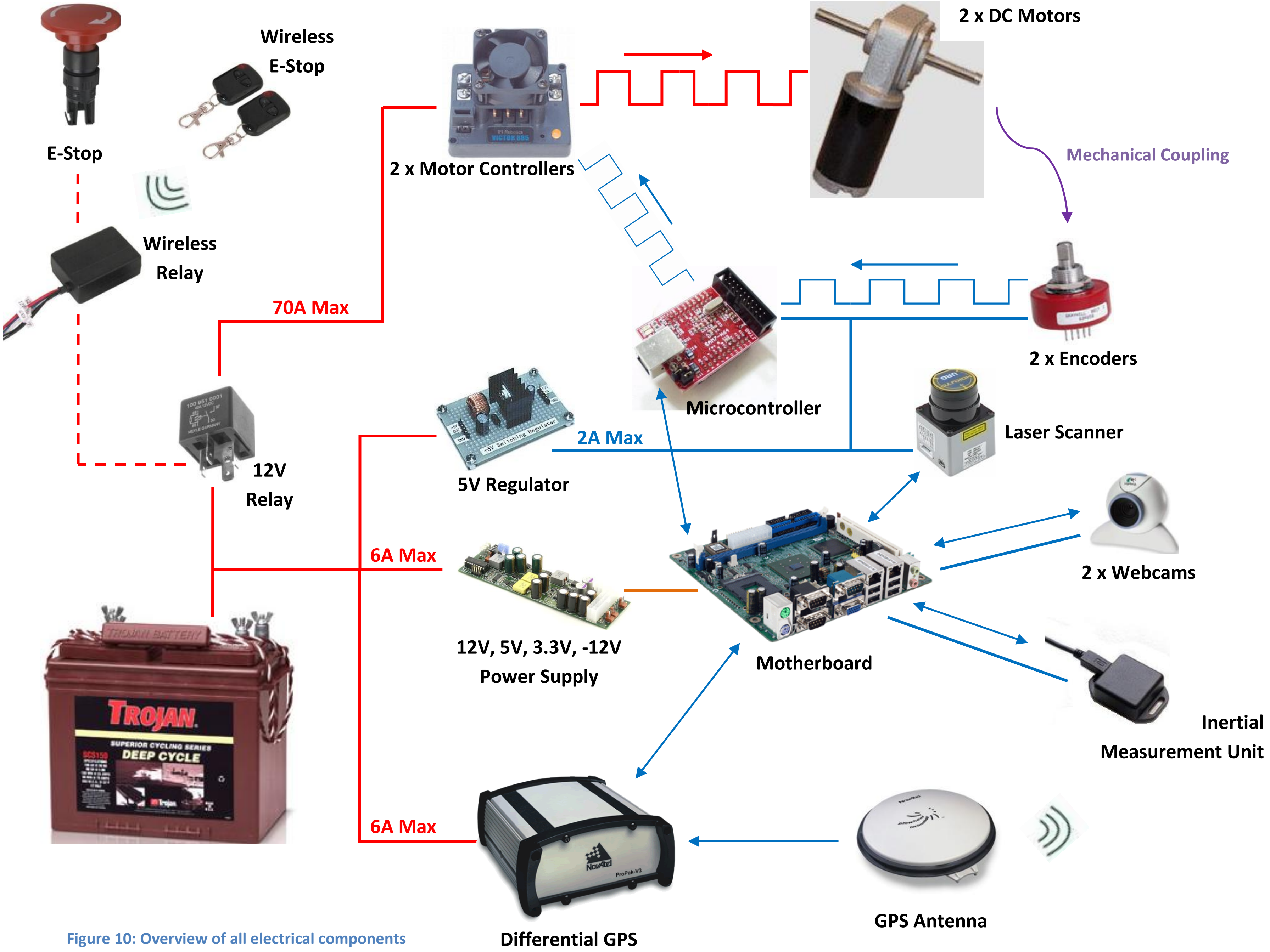

Figure 10: Overview of all electrical components

Computing

Hardware

The main computer on board Q-Bert is a Mini-ITX SBC86807 Motherboard. The mini-ITX boards were chosen for their compact size and ability to run from a 12V car battery. The motherboard is powered by a M2-ATX power supply unit (PSU). This PSU is specifically designed to handle the noise and varying voltages of a car battery. The SBC86807 motherboard was chosen because it has four RS-232 serial ports and because it already belonged to the UW Robotics Team (it was purchased for a different project two years ago). The motherboard has a 400-MHz Celeron-M processor with 512-MB of RAM.

The Mini-ITX motherboard is comparable to desktop computer, but more compact and with low power requirements. Therefore interrupt handling and PWM generation were off-loaded to a SAM-7 microcontroller. The SAM-7 is an Atmel processor based on the ARM-7 architecture. The SAM-7 is a 32-bit processor that runs at 18.432-MHz and the board has 64-kB of program flash and 16-kB of RAM. More importantly, the board has three 20-bit PWM outputs, three 32-bit timers, two UARTs, and a USB interface. The chip is programmed in C via a USB connection and a boot-loader preloaded on the chip. A UART is used to communicate with the mini-ITX board via a Maxim232 chip – the mini-ITX board has 12V RS-232 ports. The interrupt lines on the SAM-7 are used to collect and record encoder data and the PWM lines are used to send a servo-style PWM signal to the Victor-885 motor controllers. Custom software on the SAM-7 chip allows the chip to accept the desired speed from the mini-ITX board and the SAM-7 will 'ramp' the speed to the desired speed to avoid sudden acceleration and cap the top speed to 5-mph as required for the IGVC competition. Furthermore, a proportional-derivative (PD) feedback controller is used to maintain the desired speed. Finally, the SAM-7 will report the total number of encoder ticks, upon request, since the board was powered. The encoder ticks are calculated using quadrature decoding, thus forward motion increases the count and reverse motion decreases the count.

Software Architecture

As described above, the SAM-7 microcontroller is running a C program on a preinstalled boot-loader. The SAM-7 is not powerful enough to run an operating system. Instead of running Windows or Linux on the mini-ITX computer, the UW Robotics Team has chosen to utilize the power of the newly open-source QNX Neutrino real-time operating system (RTOS). Windows, Linux, Mac-OS, etc. are not real-time operating systems and will inherently present lag in a real-time robotic environment. In fact, the robot's name, Q-Bert, is derived from the fact that it has QNX at its core.

All code was written in C++ in the QNX Momentics integrated development environment (IDE). To fully realize the power of a real-time operating system, the entire program was written as various threads. These various threads, and a brief description of each, are presented in Figure 11.

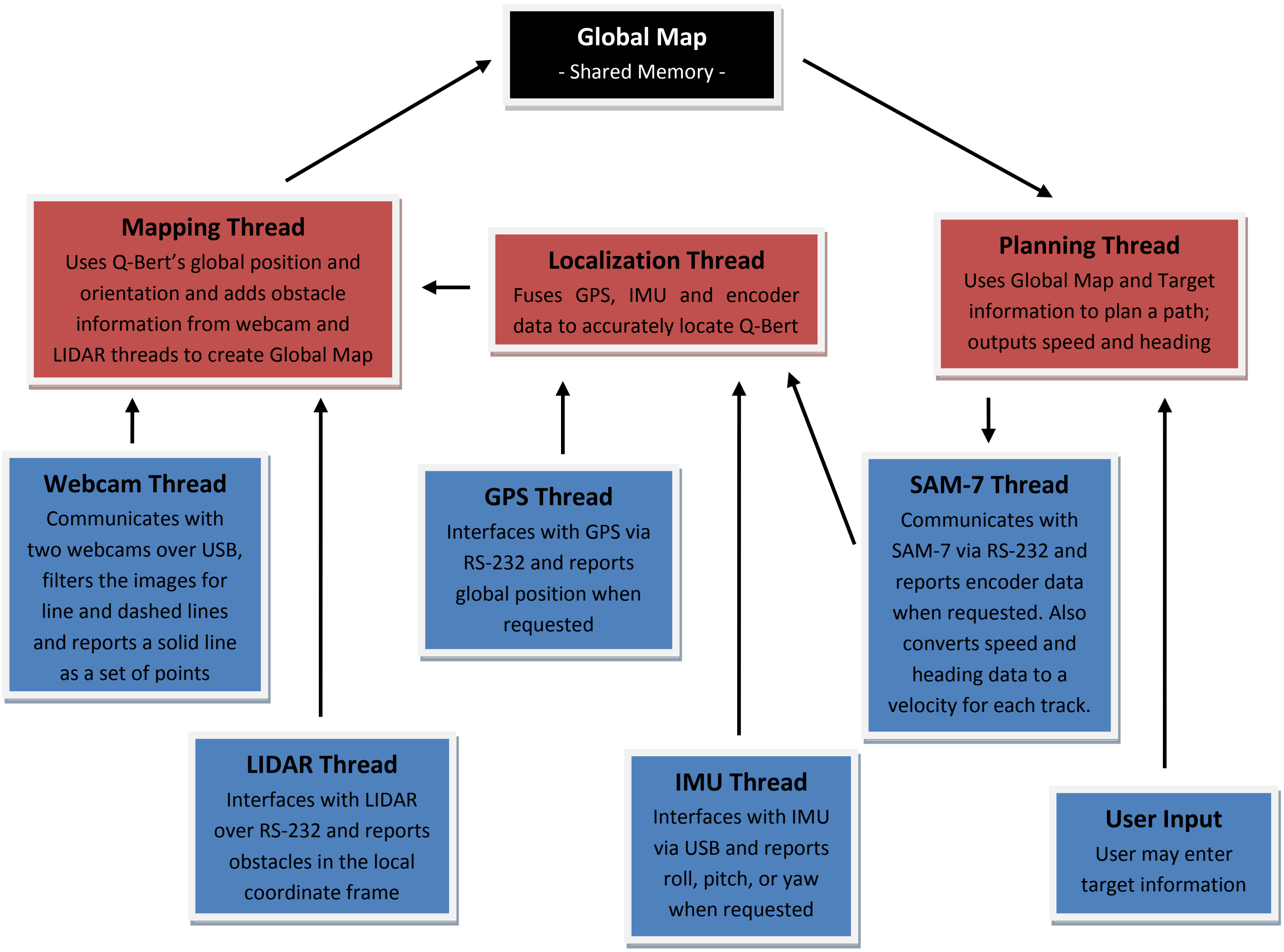

Figure 11: Description of QNX Neutrino threads

Software Design

The software for a mobile robot can be broken-down into three distinct categories: localization, mapping, and planning. Separating these three simplifies the software strategy and allows the problem to be tackled in segments. The localization and mapping are often done simultaneously and this is known as SLAM – Simultaneous Localization and Mapping. However, Q-Bert does not implement a SLAM algorithm and instead keeps the three groups separate. To further simplify the model, Q-Bert only handles each of the three categories for a two-dimensional (2D) environment. Although some obstacles may be low, like potholes, and others may be high, like a tree, all of these are projected to a 2D map. This assumption could drastically fail if the terrain were extremely steep and difficult to traverse. However, given Q-Bert's mechanical design and the fact that IGVC will not have any slopes in excess of 15-degrees, the 2D approximation is plausible.

Localization

Localization involves finding the position and orientation of the robot. Since all software is written for a 2D approximation, Q-Bert's position is only needed in the x and y directions and its orientation is only needed in the yaw, or z direction. All on-board sensors can only give the relative pose of the robot, with the exception of the dGPS receiver which uses a minimum of four satellites to determine Q-Bert's global position and various dGPS stations on Earth to correct the position for higher accuracy. Therefore the dGPS sensor is the main sensor for locating the robot on a global Cartesian plane and various other sensors are used to further refine its accuracy.

A magnetic compass could have provided a second global orientation sensor, but this was avoided because of the potentially large magnetic fields created by the motors which would heavily skew the compass's reading. Instead, an inertial measurement unit (IMU) was used to determine the robot's change in heading. The IMU internally fuses its gyroscope data and integrates it to provide a heading. Furthermore, unlike wheeled robots, Q-Bert's tracks virtually eliminate slip. Therefore the encoder data is exceptionally reliable. Consequently, when moving straight, the total number of encoder counts can be mapped to a relative distance traveled. When the robot is turning, the difference between the two encoder counts can be used to determine the robot's relative orientation. The LIDAR and cameras are used strictly for mapping and not localization as Q-Bert does not use SLAM. For 2009's IGVC competition the UW Robotics Team hopes to use these sensors to further improve localization by implementing SLAM and visual odometry.

Mapping

Once localization is complete, Q-Bert knows its location and orientation in a global reference frame. The cameras and LIDAR are then used to detect obstacles. Each of these sensors will only detect obstacles in a local reference frame and must therefore be mapped to the global reference frame. The global map is represented as a Cartesian occupancy grid where each square on the grid has an associated number that represents whether (a) no information is known about that square, (b) the square is obstacle free, or (c) there is an obstacle at that grid location. In the case of (c), the number associated with that square is increased each time an obstacle is mapped to that location. Therefore the larger the associated number, the more likely that there is an obstacle at that square. This implementation inherently accounts for error and uncertainty since squares with higher numbers are more likely to contain obstacles and will be surrounded by squares with lower numbers which arise from noise and uncertainty.

Planning

Various planning algorithms were considered. After much research, the decision was narrowed to three possible algorithms: (a) A* search, (b) a Genetic Algorithm for mobile robot path planning, or (c) Artificial Potential Fields Algorithm.

A* Search

A* Search is an optimal search algorithm designed to find a path from a starting point to a goal point given a heuristic. The simplest heuristic in the case of mobile robot path planning on a 2D Cartesian map is the straight-line distance from start to goal; thus the shortest distance assuming no obstacles. For IGVC's Navigation Challenge, this algorithm will work well since both the start and goal position will be known on the global map. For this challenge there are actually several goal positions, so Dijkstra's algorithm can be used to determine the optimal order in which to visit the goals. Again, the heuristic for Dijkstra's algorithm will simply be the straight-line distance between points. However, Dijkstra's algorithm could potentially fail in finding the optimal path since it would plan a path before any obstacles are observed. Therefore Dijkstra's algorithm is not used, but instead a Greedy Search algorithm is used. The Greedy algorithm uses the nearest goal as the current goal, but as the robot moves toward that goal and a new goal is closer, then Q-Bert sets the new goal as the current goal.

The biggest limitation to the A* Search algorithm is that it requires a goal. For IGVC's Autonomous Challenge Competition, a goal position is not given in the global reference frame (i.e. a GPS waypoint). Therefore this algorithm must be modified to account for this. Modifying the A* Search algorithm involves giving the algorithm a temporary goal position and updating the goal as more of the map is discovered. This modification could be potentially problematic since the new goal must lie within the two lines and must not be placed inside an obstacle. This is a difficult task since the robot now relies heavily on its ability to create and interpret the global map.

Genetic Algorithm

Genetic Algorithms are great for finding a good solution quickly, but they lack in finding the optimal solution. However, once the genetic algorithm determines a plausible path, the path can be optimized using a hill-climbing or local search algorithm. Realistically, the optimal solution is not required for the task of mobile robot path planning. The robot simply requires a feasible path that navigates around obstacles in a globally optimal fashion; i.e. if the algorithm can decide which side of an obstacle to go to achieve the optimal path, then it is not necessary to fully refine the path to make the path centimeters shorter. With this in mind, a genetic algorithm is quite attractive because it does not require a heuristic, and it can quickly determine new paths in a dynamic environment. Note that although IGVC-2008 does not present a dynamic environment (obstacles are stationary), it is still best to consider the environment dynamic since it is only partially observable – from the robot's perspective, obstacles 'appear' as the robot traverses the map.

The primary limitation to the genetic path planning algorithm is the same limitation that the A* Search algorithm has: it requires a goal location. Therefore this algorithm can be modified the same way as the A* Search algorithm, but as stated above, this modification has its limitations.

Artificial Potential Fields

This algorithm comes from physics; specifically the idea of potential (magnetic) field attraction and repulsion. Essentially the robot is attracted by opposing potential fields, and repelled by like potential fields, in software. Therefore once the map is created and all lines, barriers, pot holes, etc. are mapped as obstacles, then all of these are considered to be surrounded by like potential fields, thus repelling the robot. As in physics, the field's strength increases as it comes closer. Therefore, the robot is repelled by all obstacles and repelled more strongly by closer obstacles. To ensure the robot generally moves in a desired direction, attractive potential fields can be place in the direction of the line obstacles. These fields would be linear (along the line) as opposed to circular like the obstacle avoidance fields, and would have the same strength at any point. Additionally, to ensure the robot does not turn around, a repulsive field can be placed behind the robot to push it forward. However, these fields would decrease in strength over time to ensure the robot can escape a dead-end if it were to ever encounter one. Finally, in the case of the IGVC Navigation Challenge, the robot can treat each goal as an attractive circular field, where the field would be 'turned-off' once that goal is reached. The largest drawback of this algorithm is that it is not intended to find an optimal or near-optimal path. It is designed to find a safe path. However, its biggest proponent is the fact that it does not require a specified goal.

Planning Algorithm for IGVC-2008

Although each of the three planning algorithms mentioned above has its merits, the UW Robotics Team decided that the Artificial Potential Fields algorithm is best suited for both challenges presented in IGVC-2008. In practice, this decision has proven successful. The potential fields algorithm allows a great deal of flexibility by changing the strengths of the various fields. Furthermore, the mapping technique has proven quite successful and the creation of a global map is a useful debugging tool.

Conclusion

Q-Bert is a unique and successful autonomous ground vehicle. Since the robot was designed and built from scratch a tremendous number of person-hours were expended to realize the final product. These numbers are further broken-down in the *Members* table below. Given that UWRT is a student run, not-for-profit team, Q-Bert was built on a strict budget with the help of several industry sponsors; detailed in the *Cost* table below. Although Q-Bert will still be refined before IGVC-2008, some preliminary specifications are detailed in the table below. These specifications are mainly design specification, however preliminary testing has shown them to be quite accurate.

Maximum Speed	5 miles / hour (hardware and software regulated)
Ramp Climbing Ability	15° incline with 20-lbs payload
Reaction Time	< 0.5-seconds (measured)
Battery Life	2 hours
Distance at which Obstacles are Detected	4 meters
How Vehicle deals with Complex Obstacles	Artificial Potential Fields algorithm
Accuracy of Arrival at Navigation Waypoints	±0.7 meters

Cost

Item	MSRP	Cost to UWRT
Hokuyo URG-04LX Laser Scanner	$3000	$3000
NovAtel OEMV-3 GPS System	$10000	$2000
Logitech QuickCam Express Webcams (x2)	$40	$0
MotionNode IMU	$1000	$1000
GreyHill 63R Encoders (x2)	$110	$110
NPC 2212 Motors (x2)	$310	$310
IFI Victor 885 Motor Controllers (x2)	$400	$360
Trojan SCS-150 Deep Cycle Lead-Acid Battery	$180	$130
Electronics (Relays, E-Stop, etc.)	$150	$150
M2-ATX Power Supply Unit	$90	$80
Mini-ITX SBC86807 Motherboard	$250	$0
SAM-7 MCU Board	$40	$40
Various Mechanical Components	$600	$100
TOTAL:	**$16170**	**$7280**

Members

Name	Task	Program	Class of	Person-hours Expended
Rehman Merali	Higher-level intelligence	Mechatronics	2008	450
Matthew Rendall	Mechanical design/fabrication	Mechatronics	2008	450
Mark Derige	Sensor Interfacing	Mechatronics	2008	400
Kenneth Lee	Mechanical design	Mechanical	2008	250
Scott MacLellan	Low-level software	Mechatronics	2009	250
Jeremy VanderMeer	Electrical design/fabrication	Electrical	2011	100