IGVC
2010

UNIVERSITY OF
Waterloo

UW
ROBOTICS TEAM

“IOREK” DESIGN OVERVIEW

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 Iorek 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> 14 May 2010

Introduction

The University of Waterloo Robotics Team (UWRT) presents Iorek, an autonomous vehicle designed and built entirely by undergraduate students. UWRT is proud to make its third appearance at the Intelligent Ground Vehicle Competition (IGVC) in 2010.

Design Process

The overall design philosophy of Iorek was to create a modular design that enabled multiple software, mechanical, and electrical components to be designed in tandem. This methodology was chosen mainly due to the constraints of the team's organization and timeline. UWRT is comprised of many people with varying skills, experience and dedication to the team, which results in the need to divide the overall task of building the robot into many smaller tasks of varying difficulty. In addition, the co-operative education program at the University of Waterloo results in students being on campus for only four months at a time. Thus, it was important for tasks to be divided such that multiple parts can be completed at the same time.

Another important aspect of Iorek's current design is that it is an improved version of last year's IGVC entry. This means that the design process consisted mainly of identifying past problems and how we could improve them with the current design. These problems included vibration, unreliability of electrical connectors, and safety concerns. As Iorek was designed for IGVC 2010, each component of the 2009 entry was analyzed, redesigned to improve upon the problems identified, and either altered or rebuilt entirely based on the updated design.

Throughout the design process, resources were also taken into consideration, such as man power and money. Iorek's design team was a small group of dedicated members who designed the majority of the vehicle and deligated tasks when other members were available. This enabled the team to utilize their members to their full potential based on the time they had available, while ensuring that everyone gained knowledge and experience that will assist with future design projects.

Team Member	Academic Department & Class	Team Position
Megan Pollock	2B Systems Design	IGVC/ Mechanical Design Team Lead
James Servos	3A Mechatronics	Software Design Team Lead
Craig MacKenzie	3A Mechatronics	Electrical Design Team Lead
Kent Stoltz	3A Mechatronics	Mechanical Design Team Lead
Melissa Deziel	2B Management	Mechanical Design/ Fabrication
Dan Giles	2A Mechatronics	Mechanical Design/ Fabrication

Team Member	Academic Department & Class	Team Position
Steven Lao	2A Mechatronics	Mechanical Design/ Fabrication
David Nguyen	2A Mechatronics	Mechanical Design/ Fabrication
Alex LeBlanc	1B Mechatronics	Mechanical/ Electrical Fabrication
Matt Books	1B Electrical	Mechanical Design/ Fabrication
Beomjoon Kim	3A Mechatronics	Software Design/ Implementation

The cost of the vehicle is estimated in the table below which separates mechanical, electrical, and software components as well as identifying components that were purchased as opposed to designed and fabricated by the team.

Mechanical Systems and Design		**Electrical Systems Costs**	
Frame & Drivetrain	$400	4 Layer PCB Fabrication	$249
Gearboxes	$450	PCB components & ARM7 Chip (AT91SAM7)	$500
Sensor Mast	$200	Two (2) Trojan SCS-150 Deep Cycle Lead-Acid Battery	$336
Motors	$800	Two (2) IFI Victor 885 Motor Controllers	$400
Mechanicial Systems Subtotal	**$1,850**	Two (2) Mini-ITX SBC86807 Motherboard (One for Vision Processing, One for Navigation AI and Data Logging)	$516
		Samlex America SDC-23 Step-down	$125
Navigation Sensors		JR Sport 6 Channel FM Receiver	$90
SICK LMS111 LIDAR	$6,393	Four (4) Grayhill Optical Encoder 63R128	$115
NovAtel OEMV-3 GPS System	$15000 *	External Electrical System & Power System Cabling	$150
Landmark 10 IMU Gladiator Tech.	$2,495	**Electrical Subtotal**	**$2,481**
Navigation Subtotal	**$23,888.00**		
Estimated Total Cost	**$28,219**	* Approximate cost. Awaiting quote from vendor.	

The overall design upgrade process for IGVC 2010 took approximately 8 months including performance review of last year's competition, redesign, fabrication, and testing. In terms of man-hours, the project took an estimated 1400 hours to complete including the original design for the 2009 IGVC competition and the redesign for the 2010 IGVC competition.

Mechanical Design

Overview of Design

Many criteria were considered in the design process. The first was the ability to navigate effectively off-road. To effectively do this for the IGVC and further applications that would potentially require more demanding off-road capabilities, large pneumatic tires were selected. These are far superior to treads in durability, ease of use and, in most cases, traction. To facilitate excellent maneuverability 6 wheels are used, with the middle wheel lowered by ¼". This allows the center wheel to take the majority of the normal force, and therefore, the frictional force, which makes turning easier, since there is less friction (turning scrub) force to overcome while turning. It also keeps the wheel base long for climbing and stability, without adding extra turning scrub associated with a long base 4 wheel skid steer. Most components were selected based on their cost and availability. The machined components are designed to be quick to fabricate and easy to assemble to speed up the manufacturing of the entire drive train.

Overview of Iorek's Chassis

Drive Train

The drive motors are 12V minibike motors that can provide 270 Watts at maximum power. Since the possible weight of the vehicle is greater than 160 pounds, four motors are used: two powering each side. These will have their power combined in a custom single stage gearbox which uses a 15 tooth, 1.5 module gear on the output shaft of each motor, mated to a common output shaft with a 60 tooth gear (Figure 1). The output of the gearbox is a 14 tooth sprocket, which drives one continuous chain as shown in Figure 2 that wraps around the 60 tooth sprocket on each of the 3 wheels on that side. This layout allows for a single chain and two tensioners. The combination of the 4:1 Gear reduction and the 60:14 Sprocket reduction combine for a reduction from the motors of 17.14:1. This ratio, with the 2700 RPM motors and 10.5" wheels gives a top speed of 2.1 m/s (4.7 mph), which is just under the maximum for the IGVC completion.

The wheel and sprocket assemblies have integrated ¾" bearings, and so are mounted to dead axles. The axles must simply support the load created by the weight of the vehicle and the tension of the chain. It was determined that stress concentrations on the axles would be very undesirable and so a hardened 4130 shaft is used. This is shrunk fit into a mounting plate and bolted onto the frame through the close fitting holes milled in the frame. This design is very simple to machine (using undersized reamers) and is very durable.

One of the major problems that the mechanical design ran into was with the chain. The gear box sprocket was too high and the chain was rubbing against itself as it travelled over the top of the gears. In order to space out the chain from itself, idlers were added into the chain's path, holding the chain away from itself.

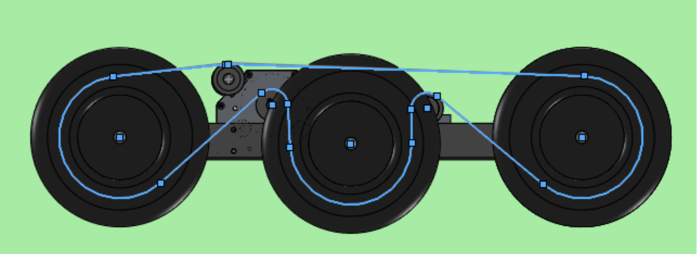


Figure 1: Side View of Chain and Centre Wheel Offset

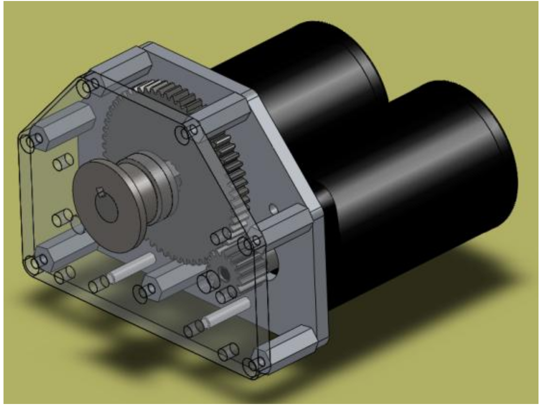


Figure 2: Gearbox Design

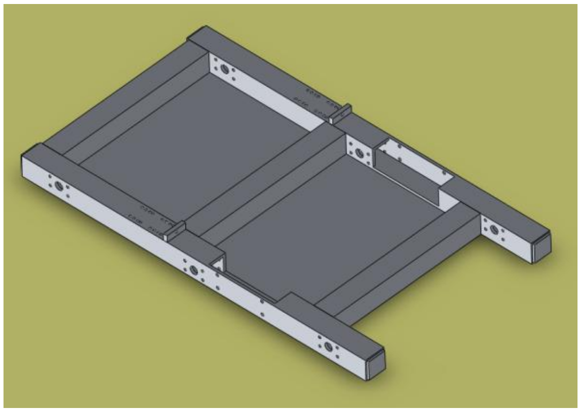


Figure 3: Frame Design

Frame

The frame is a ladder frame for maximum strength, and minimum cost and difficulty of fabrication. There are two main rails that run the length of the frame and mount most of the components: the dead axles for the wheels, and the gearboxes. These rails are subjected to serious torsion due to the cantilevered axles so a cross rail is situated as close as possible to each axle. This layout provides maximum torsional stiffness, especially since boxed tubing is being used instead of channel or angle (Figure 4). The frame is welded together with solid fillet welds, and the bottom plate is stitch-welded on. The bottom plate provides additional stiffness, and convenient mounting for the remaining components. The batteries need to be isolated from the vibration from the frame, and as such sit on a foam pad on the bottom plate, with a strap to hold them in place.

For the tower, 3/8" wall tube is used. The reasons for this are that it adds only minimal weight (~8 lbs), and increases the strength greatly, especially at welds. The tubes were increased in overall diameter from the previous design, and the design of the tower was changed. These changes were made due to stress concentrations in last year's design that resulted in the tower breaking. The design was also done in such a way that the top of the frame will be as robust and sturdy as possible, in order to decrease the vibration of the GPS as well as the vision system camera. Panels were riveted to the frame in order to hold switches which would be easy to access. Finally, an innovation of the tower is that tube mounts were welded to the frame that allowed the tower to be easily attached and detached from the rest of the robot for ease of transportation, without compromising the strength of the tower. In addition, any electronics on the tower were attached to the main chassis via a large connector in order to minimize the limitation of the wiring hindering the ability to remove the tower from the frame.

Electrical Box

The electrical box was designed to hold the boards vertically and to allow ease of access for troubleshooting. The box is made from aluminum which creates a Faraday cage to shield the electronics from electromagnetic interference generated by the high-current electronics. Rubber grommets are used on the fastening holes to reduce vibration. The electrical box is also designed to be easily opened when necessary. This is done by including a hinged lid with a handle, and chains to support the open lid from falling back and shorting the battery which is located behind it.

Layout

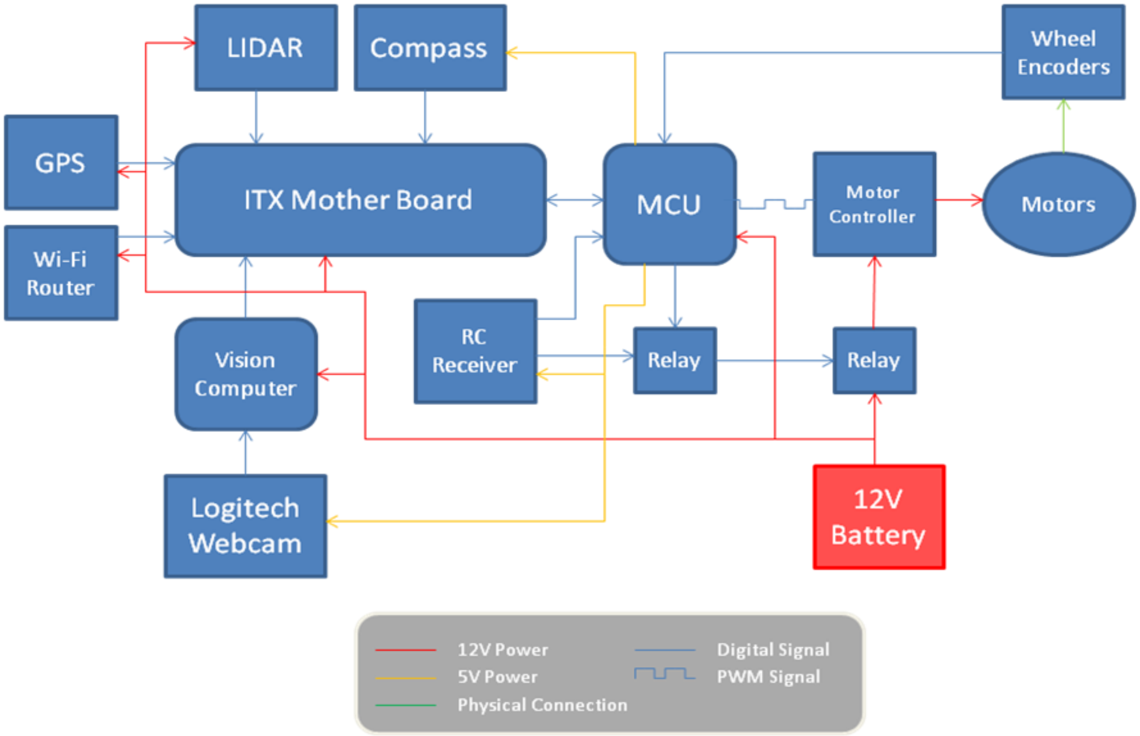
A major innovation of the mechanical design is the layout of the vehicle which was designed for maximized usability as well as functionality. The frame has a bumper welded to the front in order to protect the vehicle in the event that it hits an obstacle. The LIDAR mount is positioned such that it holds the LIDAR behind the bumper without obstructing the view of the LIDAR. The motors and encoders are positioned directly behind the LIDAR in order to keep them as far away from the electronics as possible while still in a central location of the drive train. The victor mount is also placed between the motor and is designed to keep the encoders covered and off the bottom of the vehicle in the event of rain or any other precipitation. The payload mount is also located above the motors in order to help balance the weight of the battery which is located slightly behind the centre of the vehicle. Finally, the electrical box is located at the back of the vehicle to enable easy access when testing. Most of the vehicle is enclosed by the tower which can be outfitted with a cloth covering to protect the vehicle’s electronics from being damaged by weather. This layout enables access to all electronics as well as the battery, while still distributing the weight evenly over the vehicle and protecting the delicate components of the vehicle.

Electrical Design

Design Overview

Iorek's electrical system provides power and control signals to the various subsystems within the robot. The computer system is the heart of the robot, and is comprised of a dedicated vision PC, a Mini ITX motherboard and a custom low-level MCU interface board implementing an ARM7 based microcontroller. The majority of the updates to the electrical system were encapsulated within the redesign of the MCU board. A block diagram illustrating the various interconnections within the system is provided in Figure 1 below.

Figure 1: Electrical System Block Diagram



Power Distribution

Iorek is powered by a single 12V Trojan deep cycle battery, which was chosen for its high capacity which is useful for testing. The motors are driven directly from the main 12V line through a pair of Victor 884 motor drivers. The ITX board is powered from a PicoPSU unit while the MCU board has an on board 12V to 5V switching regulator.

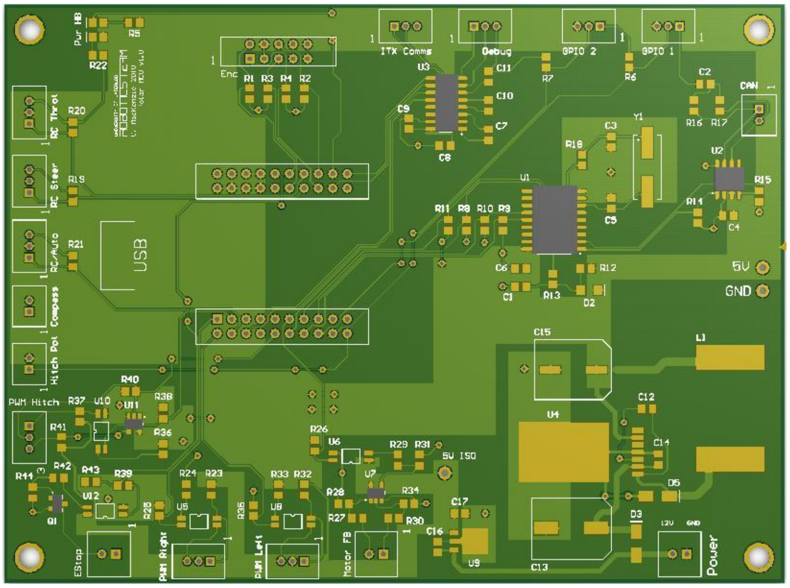
Mini ITX Computer

The path planning and localization are performed on a VIA Mini-ITX computer. The ITX board used provides a 1.0 GHz processor, 1GB RAM, laptop hard drive and a full suite of peripherals. The operating system used in Ubuntu 8.10 server edition. The LIDAR, GPS and compass are interfaced to the ITX board through a set of USB to serial converter. The ITX board interprets the sensor data and makes movement decisions, passing these instructions to the MCU board through a custom serial protocol.

MCU Board

The main control board (MCU) serves as the low level interface to Iorek's motors. The MCU receives speed commands from the ITX and uses encoder feedback to control the motors. The MCU was completely redesigned from last year. The previous revision of the board was implemented on vector board and was unstable and prone to failure. The updated design was moved to a custom PCB design, and is based on the Atmel SAM7S256 implementation of the ARM7 core. The board uses an Olimex SAM7 header board with self contained power management in order to simplify design changes and allowing the chip to be quickly swapped out should a failure occur. Power for the board is supplied from a custom 5V switching regulator designed around the National Semiconductor LM2678. The redesigned board features innovations that include custom opto-isolation circuitry for interfacing the microcontroller to the high voltage outputs of the board, as well as carefully selected connectors to ensure high voltage inputs cannot physically be plugged into digital lines. The available communication interfaces are RS-232 and a CAN bus reserved for future implementation. A model of the finished board is shown in Figure 2 below.

Figure 2: MCU Board Model



Layout

Externally, the electronics are positioned in a way that eliminates problems with signal interference. One of the major problems that was encountered with the electrical system was the large amounts of current being drawn from the drive motors which results in a large amount of electromagnetic noise. This noise would result in disruptions in the signal wires and sensors which would be near the motors or the motor wires. In order to prevent this, the sensitive sensors such as the compass and GPS were mounted on top of a tower above the robot, far away from any sources of noise. Also the high power relays are not in the electrical box so that they are separated from the electronics with an aluminum plate which acts as a faraday cage and dampens any noise from traveling to the electronics. Finally, the high power wires and signal wires are routed on opposite sides of the robot to give extra separation.

Sensors

Positioning Sensors

Encoders

Both drive axles on Iorek have an encoder mounted to them so that the distance travelled by each side can be determined. This can be used to not only determine speed and distance travelled but also rotation of the robot by calculating the difference between the speeds of each side. Working together with the GPS and compass the encoders will help determine position as well as heading. The encoders chosen are the Greyhill 63R encoders that have two channels at 128 pulses per revolution. Therefore, using quadrature decoding each axle's direction and rotation is known with resolution $360/(128x4) = 0.703^o$. Given the drive wheel diameter of 25.4cm the encoders are able to detect the robots change in position with $(\pi \times 25.4 \times 0.703)/360 = 0.156$ cm resolution.

Differential GPS

Differential GPS (dGPS) is the only sensor that can localize the robot in 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 system and 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 prohibit off-board sensors, Iorek is limited to using the available WAAS signals for correction and can therefore only achieve around 0.6 m absolute accuracy [1].

Compass

A compass is included in Iorek's sensor suite to give a reference heading in the global reference frame. The GPS can also be used to determine the robots heading but the robot needs to be moving in order to do this. The compass helps determine heading more accurately and without the need to move the robot. The EZ-COMPASS-3 was chosen for its robustness and integrated tilt sensor. The accuracy on this compass is stated to be +/- 0.25 deg [2].

Obstacle Detection Sensors

Laser Range Finder

The laser range finder is the primary sensor for obstacle avoidance; it is used detect any and all obstacles with height. The SICK PLS is an excellent sensor for mobile robotics due it its excellent performance benchmarks and durability. The SICK sensor has a 180° view and a maximum range of 50 meters. It measures with 5 centimeter accuracy and angular resolution of 0.5 degrees. This allows the robot to detect and map obstacles well in advance of encountering them.

Webcams

Iorek uses a Logitech QuickCam Pro 9000 webcam for its vision system. The webcam is mounted on the tower above the robot in center and angled downed in such a way that the top edge of the image is parallel with the horizon. The camera is used to detect non material obstacles such as lines and simulated pot holes.

Software Design

Software Strategy

The overall software strategy used on Iorek was to create a highly modular and easily configurable design. This allows for various components to be swapped in and out of the program at any given time, as well as allowing for tweaking the configuration of the algorithms in the field. This modularity is accomplished by using an event driven, multi-threaded system. This type of system also allows for many other benefits such as easily implemented unit testing and simulation.

Another key in the design of the system is the separation of the high-level state estimation, mapping, and behavior control from the low-level motor control. This separation allows for faster development, easier debugging, and a greater degree of safety and predictability.

The software contains six main components which are the knowledge base, the global path planner, the local path planner, vision processing, sensor drivers, and the core engine. Each of these entities is implemented independently such that you can easily replace any of them without needing to change any of the other implementations.

Computer Setup

ITX Board

The main control loop, sensor data and path-planning is done on a VIA Mini-ITX computer. The ITX board has a 1.0GHz processor, 1GB DDR2 RAM, a laptop hard drive, and the standard set of peripheral ports. The operating system used is the Ubuntu 8.10 server edition. The LIDAR, GPS and compass are connected to the ITX board through USB to serial converters and a USB hub. The board processes their data and makes movement decisions. The decisions are then passed on to the MCU board using a serial port and custom binary protocol.

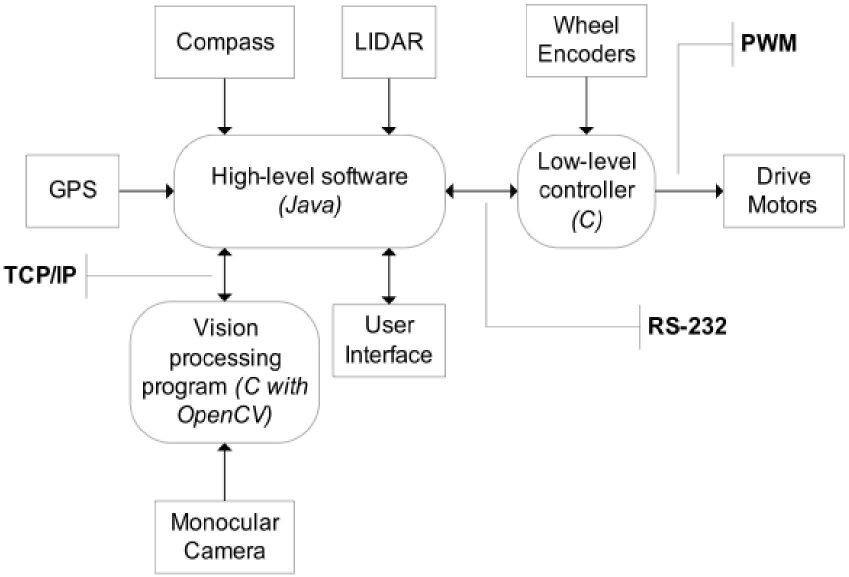
MCU Board

The main control board (MCU) is the robot's low-level control board. The board receives speed commands from the ITX board and uses encoder feedback to control the motor speeds. The MCU sets the speed of each motor by sending a servo pulse to the Parallax motor controller. In addition to controlling the robot's main motors, the MCU controls the LIDAR nodding and monitors the E-stop and the LIDAR potentiometer status. The MCU board is designed to have the following functionality:

The MCU board uses an Atmel SAM7 microprocessor (AT91SAM7S64). To simplify the board design and rewiring, an Olimex SAM7 header board is used. The header board has self-contained power management. Instead of soldering directly to the SAM7 microprocessor, the header board connects to two rows of female headers. This makes prototyping and fabrication easier since wiring a pair of headers is much easier than wiring to a 64 pin LQFP package. The header board provides access to most of the SAM7's programmable I/O pins.

Vision Computer

The vision computer is solely dedicated to the processing and transformation of the vision data. It converts the raw video footage sent from the camera to a series of line segments that represent white lines on the field. The vision processing code is written using the open-source OpenCV vision libraries and communicates with the high-level code via TCP/IP sockets.



Environment Representation

Vehicle Position

The vehicle position is represented by its global x position, global y position, and global heading. The x dimension is analogous to longitude, and the y position is similar to latitude. Both are measured in meters, with the origin at the intersection of the equator and the prime meridian. Since the vehicle is not traversing long distances, the inaccuracy introduced by assuming the earth is flat will not be an issue. Global heading is laid out in radians according to an RHS coordinate system, with 0 radians corresponding to the vehicle facing east and $\pi/2$ radians meaning north.

Though accurate vehicle positioning is not required for the navigation challenge, it is absolutely essential for the navigation challenge. To this end, an extended Kalman Filter (EKF [3]) is used to estimate the position portion of the vehicle state. The drivewheel encoders are used as the control input in the prediction step, while a combination of the GPS and compass data is used for the correction step. Simple differential drive kinematics [4] are used for the control model.

Obstacles

The LIDAR maps obstacles into a discrete occupancy grid with a resolution of 10 cm. Each grid cell stores an estimate of how likely it is that the cell is occupied. The usage of a discrete grid makes path planning around obstacles very straightforward task, since the cells can be used as nodes for a graph search.

Boundaries

To accomplish lane following, the OpenCV-based vision system receives real-time video data from the camera. Frames are first processed to enhance the contrast between the white boundary lines and the rest of the course. One approach that works reasonably well uses only the saturation channel of the image for further processing. A threshold is then applied to equalize all areas of the image that are of no concern to the lane following algorithm. Finally, a Hough transform (provided by OpenCV) finds possible lines in the image, and dominant lines likely to be course boundaries are selected from this set.

Path Following Plan

Autonomous challenge

Initial trajectories are generated simply by offsetting towards the middle of the course any lines picked up by the vision system. Where no lines are visible, the vehicle continues straight ahead.

Nav challenge

The waypoint navigation process is a straightforward one. A list of available waypoints is input ahead of time into a configuration file. When the robot starts it first determines which waypoint it is currently at and uses it as a starting node. It then calculates the shortest sequence to use in order to visit each goal.

As the vehicle progresses, an A* search is used on the occupancy grid of obstacles to determine a safe global path. The obstacles in the grid are “inflated” to prevent the vehicle from coming too close. The A* search produces a general path that the robot can follow but it also complimented by a local path planner to ensure that obstacles are avoided since the A* search can take a non trivial amount of time to complete.

A vector field histogram algorithm has replaced the potential fields algorithm of the previous year and is used as a local path planner to augment the A* search. The VFH is a very fast and reliable method which can avoid obstacles which appear unexpectedly in the robots view or if the A* algorithm is unable to find a suitable path quickly enough.

Controls

The high-level controller for both the autonomous and the navigation challenge produce a desired path for the vehicle to follow. Because of this commonality, a single controller can be tuned for both cases. The approach chosen is known as “pure pursuit,” which is suitable for low to moderate speed and directs the vehicle to follow a point on the path l_d m ahead of the vehicle (Figure 5).

$$\omega = \frac{2K\sin(\alpha)}{l_d}$$

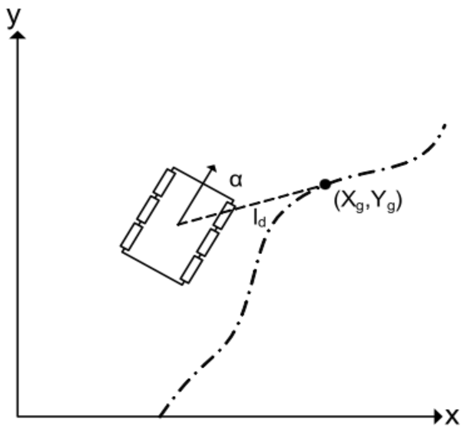


Figure 5:"Pure Pursuit" strategy

[5] provides a derivation based on a bicycle kinematic model. Since this chassis is slightly different, the equation was altered to

This produces a desired rotational velocity given angle α and a control constant K, which are passed to the low-level board along with a cruising velocity. Once on the board, they are converted into left and right wheel speed profiles based on a predefined linear acceleration. Dynamically generating a velocity profile in this way lessens mechanical stress on the drivetrain and reduces vehicle slip.

System Integration

The design of the system provides for easy system integration. There are three primary phases that will take place:

1. Mechanical Verification

   Once the drive train has undergone initial assembly, the motors will be run directly from power supplies. This will reveal any issues with the mechanical design (misalignment, for example) before additional parts are mounted to the vehicle.

2. Hardware Verification

   At this point, the mechanical operation of the chassis has been verified. The power and control wired will then be routed, the motor drivers secured and the low-level control board mounted. Then, the vehicle's speed control will be tested and tuned by using direct commands from a remote control system. This removes the dependence on high-level software during this phase of testing.

3. Operational Verification

   This is the final stage of integration, comprising the testing of the high-level control software with the now fully-assembled chassis. As before, this step builds on systems which are known to work, since the high-level software will have been previously verified in simulation and the rest of the hardware checked during the previous integration steps.

Safety

In order to maintain a safe vehicle, the chains driving the wheels were covered with sheet metal guards. All electrical components, including the batteries, are covered with a cloth cover in order to decrease shorting due to liquid, as well as to dissuade people from touching dangerous power lines and components.

All power to the system's motors is routed through relays which are used to disable the power when the emergency stop is pressed. The robot features a physical E-Stop in the form of a large red button located on the top of the robot as well a wireless E-stop implemented with a low voltage PicoSwitch relay. Both E-Stop Relays are in series so either will cause power to the motors to be cut off.

In addition to the hardware emergency stop systems, several design decisions were made to increase the reliability of the control systems themselves. First, the high-level software logs system events as they occur, in a similar way to the method used for performance evaluation. Also inherent in the architecture is the safety provided by the event-based architecture. Since each sensor driver is its own thread, failures are isolated to individual threads - the system can keep operating based on its remaining data. On top of this, the high-level kinematics module contains a watchdog timer to ensure that it is continuously being provided with inputs. If this timer expires, the module assumes that a critical error has occurred at a higher level and issues a stop command to the hardware.

This is mirrored on the low-level board. This board requires new commands to be sent at a frequency of at least 1 Hz. If this is not met, it overrides any existing commands and forces the robot to a stop. The serial protocol between the boards implements a CRC-8 checksum, and any commands with an invalid checksum are discarded.

Expected performance

Listed below are the Iorek's general specifications:

Physical Properties		Performance	
Weight	115 kg	Speed	2.1 m/s
Height	1.0 m	Acceleration	5.25 m/s^2
Width	0.75 m	Turning Radius	0 deg
Length	1.0 m	Payload	9 kg
Power Consumption		**Sensor Accuracy**	
Drive Motors	40 A	GPS	±0.6 m
LIDAR Motor	5 A	Encoders	0.703 deg
Sensors	2 A	LIDAR	± 50 mm @ 50 m
Electronics	2 A	Compass	± 0.25 deg
Total Current Draw	49 A	Webcam	30 fps
Battery Capacity	74 AH @ 50 A		
Battery Life	approx. 1.5 hrs		

Based on the above information, it is expected that Iorek will be successful in both the Autonomous Challenge and Navigation Challenge. Enormous effort has been expended on innovative design with the goals of the competition in mind. Some expected benchmarks are:

- Cruising speed: 2.0 m/s
- Speed control: Within 0.05 m/s
- Terrain: 20^o incline
- Localization accuracy: 0.6 m position, 1 degree heading
- Closest point of approach to obstacles: 0.25 m

Conclusion

Iorek is a highly robust and capable autonomous vehicle that is the result of tremendous student effort. In addition to being a complete entry into this year's Intelligent Ground Vehicle Competition, Iorek serves as a platform for future improvements and modifications. UWRT looks forward to more exciting opportunities involving Iorek.

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