YCP Robot

Tori Bare, Cory Boyle, Jason Cluck, Drew Wicke

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Abstract

Using the Robot Operating System (ROS), algorithms were developed for obstacle avoidance, and 3D navigation. Additionally, a simulator was created in OpenGL that was used as a testbed for these algorithms.

Introduction

One of the goals of the Robot Operating System (ROS) is to provide roboticists a software platform for specific robots. ROS is beneficial in this way because it creates "a wide variety of frameworks to manage complexity and facilitate rapid prototyping of software for experiments, resulting in the many robotic software systems currently used in academia and industry"[12]. This paper addresses the construction of a new ROS package that controls the X80SVP robot. The package, which already implements obstacle avoidance and wandering behavior, provides low level drivers up to a robust development framework that can be extended.

Another goal of the ROS community is to provide simulation software to test the robot. For example, the player project consists of Player, a robot interface, Stage, a two-dimensional robot simulator, and Gazebo, a three-dimensional robot simulator. As part of the project a new simulator for ROS was developed that can be extended and provides a Kinect sensor.

The first part provides a background detailing the devices, algorithms and libraries that were used; the second part discusses the design of the system following with implementation details; finally, it concludes with an overview of future work.

Requirements

Background

Various devices, technologies and algorithms were used to create an autonomous robot. The robot that was used was an X80SVP. It was chosen because this was the robot that was being considered for use in a future robotics course at YCP. A Beagleboard hosted the software and acted as a bridge to the robot while the Robot Operating System provided a framework for the software. Braitenburg aggression behavior was used to provide obstacle avoidance and a Kinect was used to provide vision. Lastly, OpenGL was used to provide 3D graphics for the simulator.

Devices

The X80SVP Robot has a max speed of 75 cm/s, weighs 3.5 kg, has a max payload of 15 kg, and has a three hour battery life. The robot also has IR and ultrasonic range sensors, as well as pyro-electric human motion sensors as seen in Figure 1.

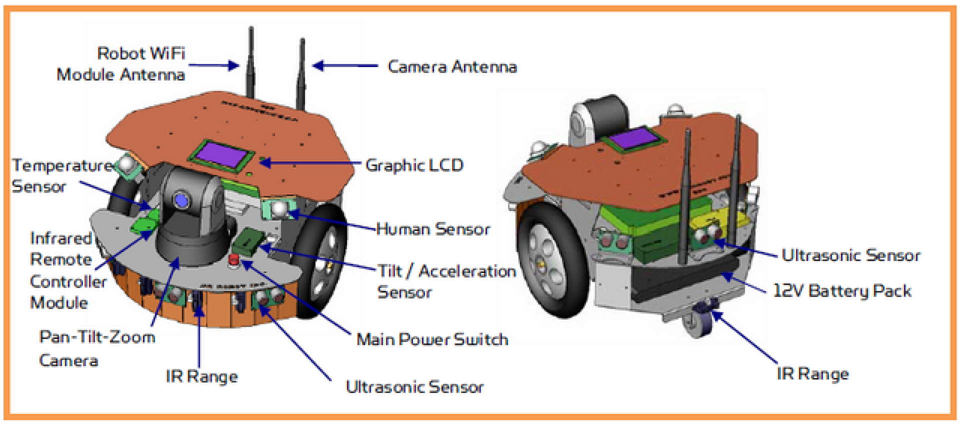


Figure 1: X80SVP Robot [5]

The Beagleboard XM was chosen as the computer for the X80SVP. The Beagleboard has many peripheral options, a 1 GHz CPU, a DSP, and it is very popular in the open source/ROS communities. The initial plan accounted for the DSP being able to process the Kinect vision data while the CPU handled the overhead associated with ROS. The major components on the board are shown below in Figure 2.

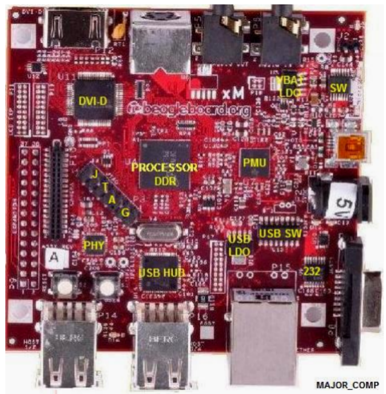


Figure 2: Beagleboard's Main Components [1]

A Kinect was used to generate maps of the robot's surroundings and to allow the robot to navigate intelligently through his environment. The OpenNI drivers for ROS, created by the makers of the Kinect, would enable the Kinect to be used in this manner. One of the main concerns with using the Kinect was the processing power that it would require. The Kinect produces a message that is roughly 1 MB at a rate of 30 frames per second, this equates to the Kinect sending about 30 MB of data each second. At first, it was expected that the DSP on the Beagleboard would have been able to handle the Kinect's processing; however, due to the overhead of ROS, the processing will most likely have to be offloaded to a netbook.

ROS

ROS is a framework that facilitates the construction and execution of applications for robots. "It provides hardware abstraction, device drivers, libraries, visualizers, message-passing, package management, and more" [3]. There are implementations of ROS in C++, Python, Lisp, Octave, and Java. ROS was chosen to act as the framework for the project because it provides a good communication model, a well structured programming environment, and an implementation in Java.

ROS executables are called nodes and are the main source of communication. ROS provides a master node called Ros Master that oversees running nodes and a parameter server, it also acts as the matchmaker for nodes and topics as seen in figure 3. ROS nodes can communicate using topics, which are similar to named busses which offer a publisher/subscriber type communication model. Nodes publish messages on topics which other nodes can subscribe to in order to receive the information being published. However, the nodes only know the name of the topic and not the name of the other node as seen in figure 3. A message's fields are described using the YAML language, a "human friendly data serialization standard for all programming languages" [6]. ROS can then convert the message file into a file that the targeted language can use, such as a header file in C++. ROS uses this message passing communication model because it is language independent and allows for "unidirectional, streaming communication"[3].

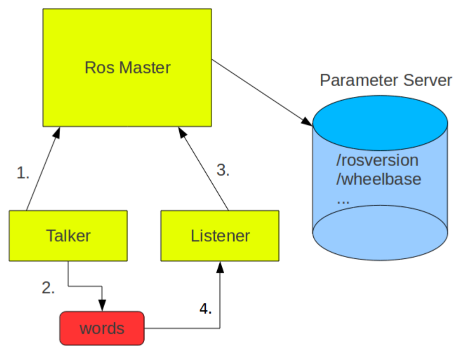


Figure 3: 1. The Talker node lets the ROS Master know that it wants to publish to the words topic and then Talker starts publishing to words. 2. Listener lets Ros Master know that it wants to subscribe to the words topic. 3. Ros Master pairs Talker and Listener so that Listener can start receiving messages on the words topic. The Parameter Server is similar to a registry in that it stores state information which nodes can access.

ROS also provides a hierarchical packaging based structure to group common elements as seen in figure 4. Nodes, the executables, that have similar roles are grouped into a package. Packages that share a common purpose are grouped into a stack. Stacks can contain one or more packages. Therefore, ROS's goal is to build a complex system out of simple, single-purpose parts[3].

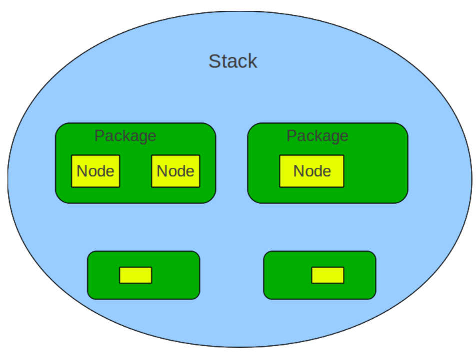


Figure 4: An illustration of the hierarchical structure of ROS. There are no limits on the number of packages per stack and no limit on the number of nodes per package.

Java's object oriented structure complements ROS's goal of complexity out of simplicity. The rosjava stack is the first implementation of ROS in Java and "developed at Google in cooperation with Willow Garage" [2]. It was chosen to allow future students in robotics the ease of use that Java provides, as well as for Java's cross platform capability. The rosjava implementation is similar to the other ROS implementations in that it provides the same communication framework and packaging structure. However, in order to integrate with other languages ROS messages are converted to classes and stored into Java jar files. The jar files can then be imported a class and the messages data types can then be used in communication over topics. Unlike other implementations, rosjava also provides its own ROS master allowing it to run on devices that only allow Java, such as an Android phone.

Obstacle Avoidance Algorithm

There are two main ways to implement obstacle avoidance, motor fusion and sensor fusion. Motor fusion also termed reactive control uses a direct correlation from sensor readings to motor velocities without any intermediate representation, such as a map[9]. The main advantage to using motor fusion is its ability to function well in real time systems. Motor fusion or "reactivity is essential for any system operating in a dynamic, uncertain environment"[15]. However, when a robot has many sensors which map to a motor command the processing time increases and therefore decreases the usefulness of motor fusion.

Sensor fusion uses the sensor data to reconstruct the surroundings to produce motor commands. The reconstruction could be in the form of a map of the environment which can then be used to avoid obstacles and possibly provide for higher level goals. Therefore, sensor fusion provides higher level functionallity than motor fusion. However, the main disadvantage of sensor fusion is due to translating the sensor data from various sensor sources which "further complicates the selection of methods, uncertainty representations, and assessments of performance" [10].

For the X80SVP robot, obstacle avoidance was accomplished by a motor fusion algorithm utilizing Braitenburg's aggression behavior. Motor fusion was chosen because the robot's sensors were unreliable and limited therefore making the sensor fusion model inappropriate. Also, Braitenburg's algorithm does not rely on the type or variety of range sensors to provide obstacle avoidance.

Braitenburg behaviors are a form of synthetic psychology described in[8]. These behaviors were thought experiments into how different emotions, such as fear, aggression, and love, can provoke movement based on sensor stimulation. Aggression behavior is caused by pairing the sensors and motors on opposite sides through a non-decreasing function as seen in figure 5.

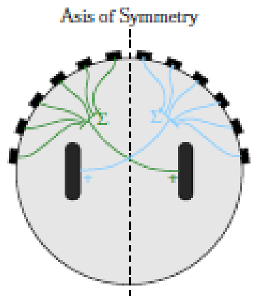


Figure 5: Braitenberg aggression behavior [14].

To implement aggression behavior for obstacle avoidance, only the front sensors are used and also modifications to use a centered sensor were made to the algorithm presented in [14]. The algorithm computes both the linear and angular velocity for the robot given the normalized sensor readings as shown in equations 1 and 2. For example, when the no obstacles are present the robot will move forward at max velocity. However, if there is an obstacle that is closer to one side of the robot then the motor on that side will spike causing the robot to rotate and avoid the obstacle. Accounting for the center sensor separately allows the robot to avoid deadlock while in symmetric corners. The value of a sensor increases as an obstacle gets farther away and as the velocity becomes greater in that direction, providing a smooth wandering movement that effectively avoids obstacles.

$$\alpha_S(t_k) = \sum_{i \in L \cup R} w_i^{\alpha_S} \hat{r}_i^S(t_k) \tag{1}$$

$$\beta_S(t_k) = \sum_{i \in R} w_i^{\beta_S} \mathfrak{D}(\theta_i') \hat{r}_i^S(t_k) - \sum_{i \in L} w_i^{\beta_S} \mathfrak{D}(\theta_i') \hat{r}_i^S(t_k) \tag{2}$$

α_S and β_S are the normalized translational and rotational speeds in the range [0,1] and [-1,1] respectively. $w_i^{\alpha_S}$ and $w_i^{\beta_S}$ are constant weights corresponding to the i^{th}sensor defined in equations 3 and 4. $\hat{r}_i^S(t_k)$ is the current normalized filtered range value of the i^{th} sensor. $\mathfrak{D}(\theta_i') = 90 - |\theta_i|$ the angular distance. Where θ_i is angle from the x-axis to the sensor assuming the x-axis lies on the axle and y-axis divides the robot in half.

$$w_i^{\alpha_S} = k_i^{\alpha} e^{-\frac{\mathfrak{D}(\theta_i')^2}{2\sigma_\alpha^2}} \tag{3}$$

$$w_i^{\beta_S} = k_i^{\beta} e^{-\frac{\mathfrak{D}(\theta_i')^2}{2\sigma_\beta^2}} \tag{4}$$

k_i^{α} and k_i^{β} are normalizing constants so that the speeds are normalized. σ_α^2 and σ_β^2 are the variance chosen here to be 1400 and 350 respectively in order to place a greater weight on small angles and less weight on greater angles as can be seen in figures 6 and 7.

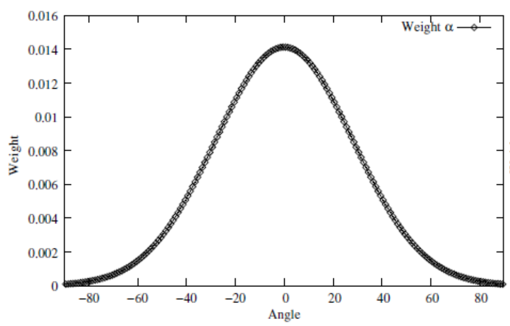


Figure 6: Weights for $\alpha_S(t_k)$ [14].

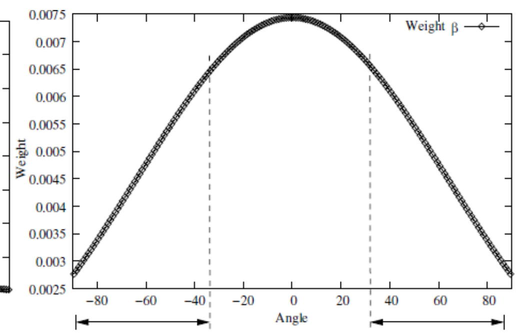


Figure 7: Weights for $\beta_S(t_k)$ [14].

Simulator

A simulator was developed to fulfill the use case of being able to test the navigation algorithms in a clean virtual environment before deploying them to the actual robot. The simulator uses OpenGL to model the robot and environment. OpenGL generates a depth-map as part of its rendering process and this is used to compute distances from the robot in any direction to other objects in the environment. This makes it possible to simulate virtual versions of the real sensors by rendering the viewport from the perspective of the sensors and reading the depth-map to determine the simulated sensor value.

The simulator uses a number of libraries to make the OpenGL API more manageable. The Free OpenGL Utility Toolkit (freeglut) is used to provide the basic windowing functions for the GL application. The OpenGL Utility Library (GLU) provides utility functions for computing projection matrices, used to create the perspective camera views. The Simple OpenGL Image Library (SOIL) is used to provide texture-loading capabilities. The simulator also interfaces directly with the X.Org Server APIs for some functions in handling mouse and full-screen controls. A custom loader was written to load DirectX format mesh files as exported by Blender. This allows environments as well as movable obstacles of completely arbitrary design and complexity to be modeled quickly, thus it can be adapted for different testing scenarios

Design

The design model favors modularity and simplicity to create a complex system. The goal was to follow the subsumption control architecture to create a “robust and flexible control system"[13]. Subsumption control architecture is a layered approach to providing control. Each layer adds increased functionality without needing to change lower levels of control.

By following the model view controller (MVC) design pattern, the implementation is extensible[11]. As seen in figure 8 the model is based on the ROS parameter server in which the model of the robot and communication layout is stored. Therefore, allowing different robot settings to be changed without affecting any of the view or control code. By following MVC different views, such as a simulated environment or the real world to be smoothly interchanged. The controller classes compose the design model. These act to move the robot, changing the robot's view.

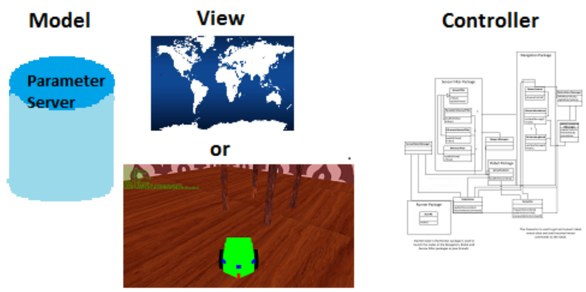


Figure 8: The model of the system is stored in the parameter server. The view can be either the world or the simulator. The controller portion is described by the classes in the design model.

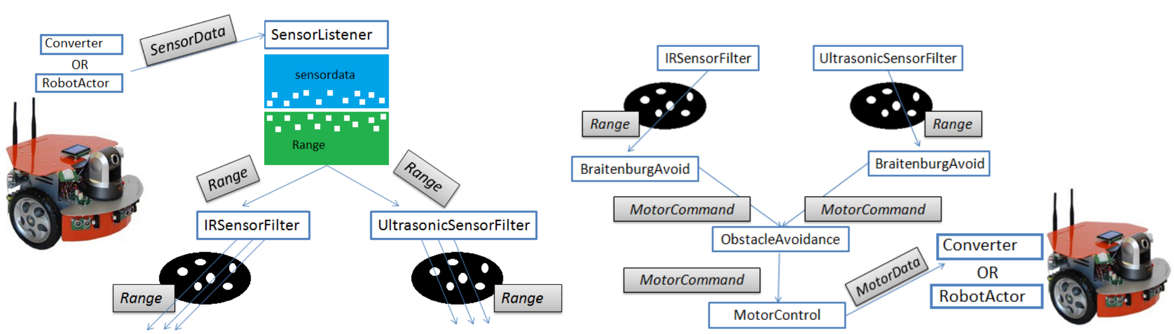


Figure 9: Simplified Design and Communication Model

The design is centered around the Converter and the RobotActor classes as s. Converter and RobotActor are interchangeable bridges between the view and the control, they publish the sensor data and send commands to actuate the robot's motors. The SensorListener class subscribes to the sensor messages published by a bridge class and publishes converted sensor data in the ROS standard Range message type.

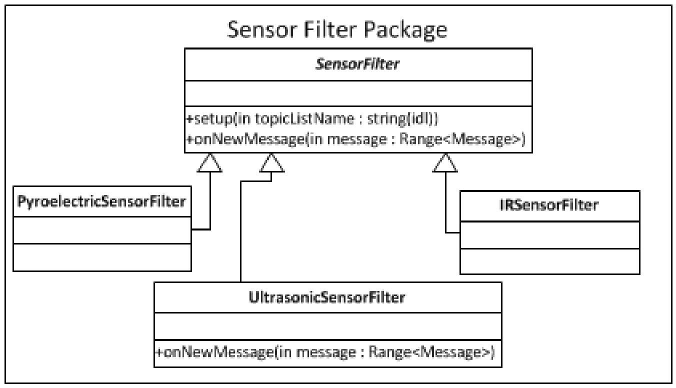


Figure 10: Diagram of the Sensor Filter package.

The SensorFilter classes filter the sensor data so that the data is more useful and the BraitenburgAvoid class uses the filtered sensor data to publish a MotorCommand message based on the Braitenburg aggression behavior algorithm. The ObstacleAvoidance node publishes a linear combination of the MotorCommand sent by the infrared and ultrasonic based on BraitenburgAvoid nodes. Finally, the MotorController acts as both an arbiter of motor commands and as a gateway back to the bridge nodes.

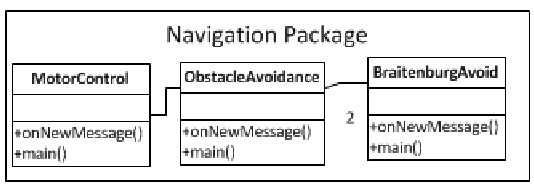


Figure 11: Diagram of the Navigation package.

Simulator Design

The initial design of the simulator relied on existing code which supported only one "Player" with one graphical view; this was adapted to support an arbitrary number of "Actors", each with any number of "Sensors". This was then used to implement each of the ultrasonic and infrared sensors as well as the graphical displays. Multiple actors allow the user to view the environment from the perspective of the robot or from an independent Camera actor, it also allows Obstacle actors to be positioned in real-time. A diagram of the simulator appears in Appendix B.

Implementation

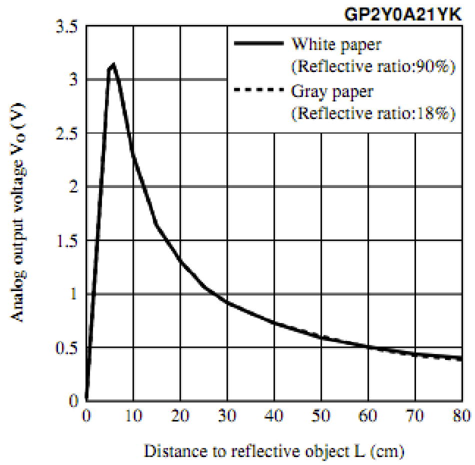
The implementation of the design was completed in both C++ and Java. C++ was used for the simulator, sign language recognition, and the serial communication between the robot and Beagleboard. Java was used to implement the rest of the design which includes a converter to standard ROS message data-types, an ultrasonic sensor filter, obstacle avoidance algorithm, and motor control arbiter.

The serial library used the PMS5005 protocol which allows any processor, DSP, or PC to control the robot through the Universal Asynchronous Receiver/Transmitter (UART) communication interface. The basic packet outline, shown in Figure 12, handles both the sensor and motor data transmission. The library that implements this interacts with ROS by subscribing to motor controls and publishing sensor data. Using this packet structure, a large amount of information can be processed every tick.

STX	RID	Reserved	DID	LENGTH	DATA	CHECKSUM	ETX

Figure 12: Packet format for serial library

The sensor and motor data from the packet structure were not ideal for our purposes and needed to be converted to useful formats. The data for the sensors needed to be handled differently for each type of sensor. The ultrasonic sensors were the most straightforward since the control board returned the distance in the range of 0 - 255 cm, which is already in the correct units for the message. The infrared sensors needed to be converted since they return a non-linear voltage value corresponding to a range of 10 - 80 cm. The voltage output with respect to distance is shown in Figure 13. This voltage output needed to be linearized using an interpolation equation [7]. The result of such an equation with respect to Analog/Digital Converter (ADC) values is shown in Figure 14. After testing the human sensors, it was decided that these will not be used at this point due to unreliable results.



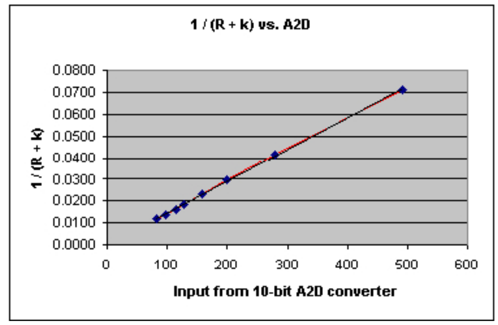


Figure 14: Linear interpolation of Voltage with respect to ADC

Figure 13: Infrared sensor voltage output from [4] values from [7]

Once the serial library and sensor conversions were implemented on a desktop system, the next step was to achieve this functionality on the Beagleboard. The Beagleboard was loaded with Ubuntu 11.10 since this OS works best with ROS. Some of the configuration scripts for ROS require Internet access so a wireless internet connection was part of the Beagleboard setup. ROS was compiled from source on the Beagleboard because cross compiling is not recommended for ROS yet. After configuring the installation, it quickly became apparent that the overhead associated with ROS was more than expected. At the moment, the Beagleboard is unable to support ROS at 10 Hz and further testing will conclude whether this can be fixed or not.

High Level Software

The Braitenburg obstacle avoidance algorithm produces linear and angular velocity values, but the robot requires left and right wheel velocities which can be converted using the differential drive kinematics equations 5 and 6. Note that $\alpha_S(t_k)$ and $\beta_S(t_k)$ are normalized linear and angular velocities defined in equations 1 and 2 and d is the wheel base of the robot.

$$V_L = \frac{2\alpha_S(t_k) + d\beta_S(t_k)}{2} \tag{5}$$

$$V_R = V_L - d\beta_S(t_k) \tag{6}$$

Ultrasonic sensors were used to provide obstacle avoidance, however the sensors can overestimate the distance to a flat wall due to specular reflection as seen in figure 15. Over estimation can happen when the sonar bounces off the wall and never returns back to the sensor causing the robot to believe that there is free space in front of it.

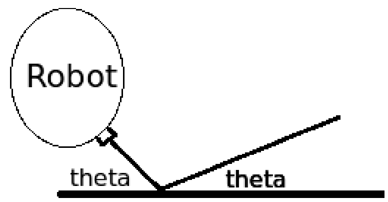


Figure 15: Specular reflection of ultrasonic sensor.

These readings can be improved by applying an incremental filter (Equation 7) as described in [14]. The filter works by acting as a short term memory to ensure that a current reading of free space is correct based on the previous range. For example, consider a robot that is approaching a wall as in figure 15 and the readings are all less than the max range of the sensor. Then specular reflection occurs causing a max range reading. The filter in equation 7 will recognize the false max reading and use the previous filtered range value instead.

$$\tilde{r}_i(t_k) = \begin{cases} r_i^s(t_k) & \text{if } r_i^s(t_k) < r_{nr}^s \\ Min\{\tilde{r}_i(t_{k-1}) + r_{\triangle}, r_{nr}^s\} & \text{if } r_i^s(t_k) = r_{nr}^s \end{cases} \tag{7}$$

$r_{nr}^s$is the max range of the sensor, $r_i^s(t_k)$ is the current range measurement, $\tilde{r}_i(t_k)$ is the current filtered range value and $\tilde{r}_i(t_{k-1})$ is the previous filtered value. $r_{\triangle}$ is a constant which is used to offset the previous value and was chosen to be 20cm as described in [14].

For every ROS node a new process is created, since a node is an executable. Therefore, in the initial implementation of the project, every rosjava node started a new process. However, the creation of new rosjava nodes poses a problem due to the overhead of creating a new Java Virtual Machine (JVM) for each node. A later implementation of rosjava implemented the solution to the problem, which was to use a thread for each node, rather than creating a new process. By using threads to encapsulate nodes, only one JVM was started. Therefore, decreasing both the launch time and overhead of starting the nodes.

RGBDSLAM was selected as the main algorithm to implement mapping. In order to take advantage of RGBDSLAM, the entire project had to be downgraded from using ROS Electric to ROS Diamondback and from using Ubuntu 11.04 to Ubuntu 10.10. RGBDSLAM allows a point cloud of the environment to be created from the Kinect data as seen in Figure 16. Once a point cloud was generated, it could be converted to an OctoMap as seen in Figure 17, a 3D occupancy grid map that is developed from an octree. The OctoMap is then sent to the 3D navigation algorithm so that the robot can utilize the map.

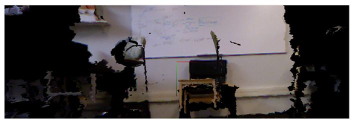


Figure 16: RGBD point cloud

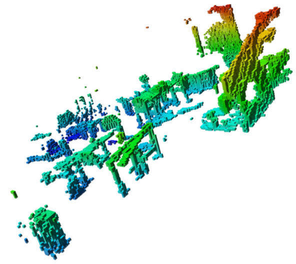


Figure 17: Octomap

The original goal was to have the robot using a static OctoMap to navigate his environment, and eventually implement dynamic mapping so the robot would have been able to map his environment while he wandered. Due to issues with ROS running in a timely matter on the Beagleboard, it is unsure as to whether the OctoMaps will be usable. At this point, a sign language feature may be replacing the OctoMaps, but that will be more-so determined in the final paper.

One of the initial challenges encountered in writing the simulator was that the position of the robot was represented as a point on an X-Y plane, but the input coming in from ROS would be in the form of differential wheel movement commands. Finding the necessary equations proved to be a challenge. It was also difficult to test initially since the ROS interface had not yet been implemented to a working degree. Some revisions and corrections had to be done once it was possible to send specific commands from ROS and to observe whether the resultant location of the robot in the simulation was correct.

Figure 18: Simulator in third person view

There were also additional problems to address with respect to speed and optimizing conversions of depthmap and point cloud data. One of these problems was in computing a linear representation of the depth map because GL uses a logarithmic representation when rendering, while the Kinect provides a linear one. The initial implementation was very inefficient in that it did the per-pixel transformations once for each needed source, including the visual display, and ROS topics for depth maps in two formats and the point cloud. This was improved significantly by making the simulator render the scene once, at the Kinect hardware's resolution. The conversion was done to this and scaled to fit the size of the visualization window rather than doing the render and conversion another time. There was also a large performance penalty to doing the conversions for each output in separate loops. This required a major refactor of the code to merge all of the conversion loops. The final version was further optimized by tracking what ROS topics are in use and only computing the data necessary to publish them.

Figure 19: Simulated Kinect depth map

There were also some modifications in what is rendered during each pass. The simulator visualization targets a frame rate of 30 fps, which is necessary for the visual output and Kinect video data simulation, but was unable to attain that rate on the workstation with all rendering passes active. Since the Sensing/Motion Controller on the robot only functions at 10 Hz, it is only necessary to broadcast sensor data to ROS at that rate; thus, the rendering passes needed for computing sensor data could be skipped on 2/3rds of the frames, saving processing resources and boosting frame rate. A useful optimization here would be the ability to do the rendering passes asynchronously, which would allow for less jitter in the frame rate caused by the combined passes doing unequal amounts of work, however this would require a machine with dual graphics cards.

Future Work

In the future, there are plans to implement features such as more advanced gesture recognition, a multi-agent system of physical robots, and using rosjava on Android to teleoperate the robot.

Gesture recognition is one of the more immediate future plans for the robot. A ROS stack called hand_interaction, created by the Massachusetts Institute of Technology, appears to be the best option for implementing this feature. Using hand_interaction, the location of the hands can be determined. As a gesture is made, the movement of the hands will be tracked and used to control the robot's behavior.

The system could be extended by adding robots, such as TurtleBots, to create a multi-agent system. Capture the flag could be a way to explore algorithms involved in multi-agent systems. However, due to the limited processing power of the Beagleboard, there would be considerable challenges implementing efficient navigation, SLAM, and learning algorithms. One solution would be to use a remote computer to perform these features.

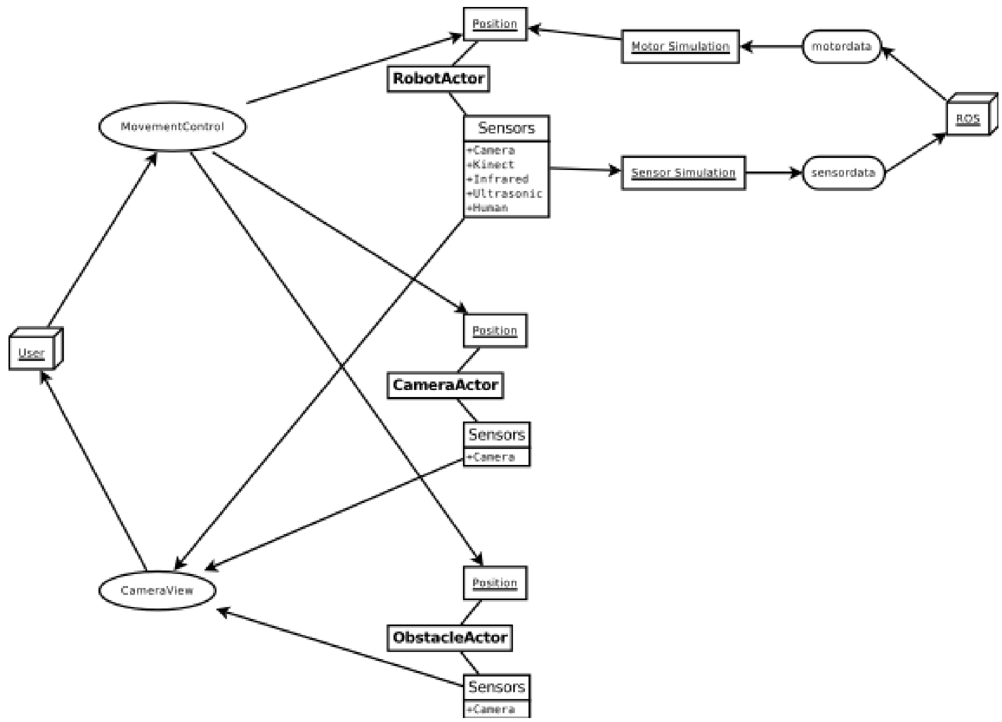
Another way the system could be extended is by using the Kinect for facial and object recognition. This would allow for high level behavior and learning rather than the current reactive-based system; however, the processing capabilities of an on-board computer may be overwhelmed.

A future system could also utilize rosjava's ability to operate on Android to provide a user with the ability to teleoperate the robot or provide the robot access to the cloud.

Appendix

Section A

The User can select to control any Actor's position. The specific sensor the CameraView is rendered from can also be selected. Data from ROS is also used to control the RobotActor's position and the Sensors are output back to ROS.



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