COOPERATIVE CONTROL OF HETEROGENEOUS MOBILE ROBOTS NETWORK

Gregory Bock, Brittany Dhall, Ryan Hendrickson, & Jared Lamkin
Project Advisors: Dr. Jing Wang & Dr. In Soo Ahn
Department of Electrical and Computer Engineering
November 24th, 2015

Outline

I. Introduction
II. E-puck Progress – Brittany
III. Kilobot Progress - Jared
IV. Qbot Progress – Ryan & Greg
V. Summary & Conclusions

I. Introduction

Problem Description

- Design cooperative control algorithms for heterogeneous groups of robots
- Implement algorithms on different robot platforms

Objectives

- Design and Experimental Validation of Cooperative Control Algorithms
  - Sensing/communication between robots
  - Implementation of local flocking control algorithms
  - Implementation of local formation control algorithms

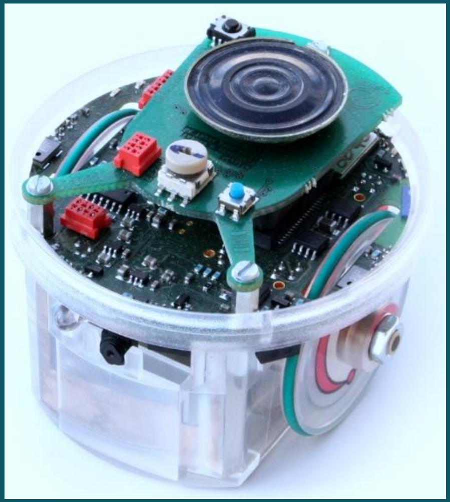
Solution

- Cooperative control algorithm design
  - Linear model
  - Non-linear model
- Deployment and validation through experimental testing
  - Modular design
  - System integration

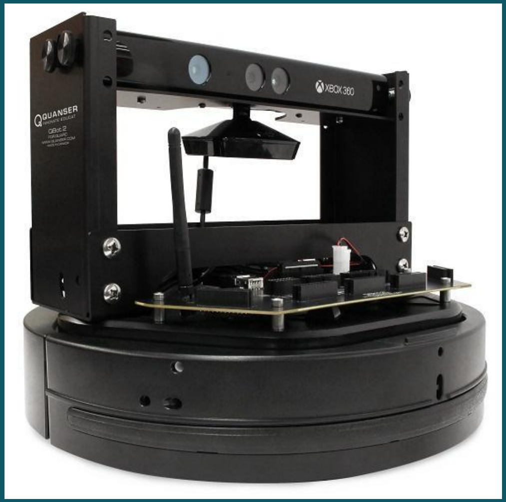
Algorithm Test Platforms

Kilobot

E-Puck



Qbot



http://www.k-team.com/mobile-robotics-products/kilobot
https://en.wikipedia.org/wiki/E-puck_mobile_robot
http://www.mathworks.com/products/connections/product_detail/product_101072.html

Division of Labor Overview

Individual Behavior	Kilobots	Jared
	Qbots	Ryan/Greg
	E-pucks	Brittany
Individual Communication	Kilobot - Kilobot	Jared
	Qbot - Qbot	Ryan/Greg
	E-puck - E-puck	Brittany
Integrated Communication	Kilobot - E-puck	Jared/Brittany
	Kilobot - Qbot	Jared/Ryan/Greg
	E-puck - Qbot	Brittany/Ryan/Greg
Algorithm Design	Linearization Based Model	Jared/Brittany/Ryan/Greg
Integrated Behavior	Formation Control Behavior	Jared/Brittany/Ryan/Greg
	Flocking Behavior	Jared/Brittany/Ryan/Greg
Testing	Software Implementation	Jared/Brittany/Ryan/Greg
	Hardware Implementation	Jared/Brittany/Ryan/Greg

II. E-puck Progress - Brittany

Gantt Chart – Work Accomplished

Task Name	Group Member Responsible for Task	Finish by Date	Oct-15			Nov-15			
			13	20	27	3	10	17	24
Research E-puck Sensors	Brittany	October 26, 2015							
Research E-puck Communication Protocol	Brittany	November 16, 2015							
Research/Test E-puck - E-puck	Brittany	December 14, 2015							
Test Kilobot - E-puck	Jared/Brittany	December 14, 2015							
Test E-puck - Qbot	Brittany/Ryan/ Greg	December 14, 2015							

Completed In progress

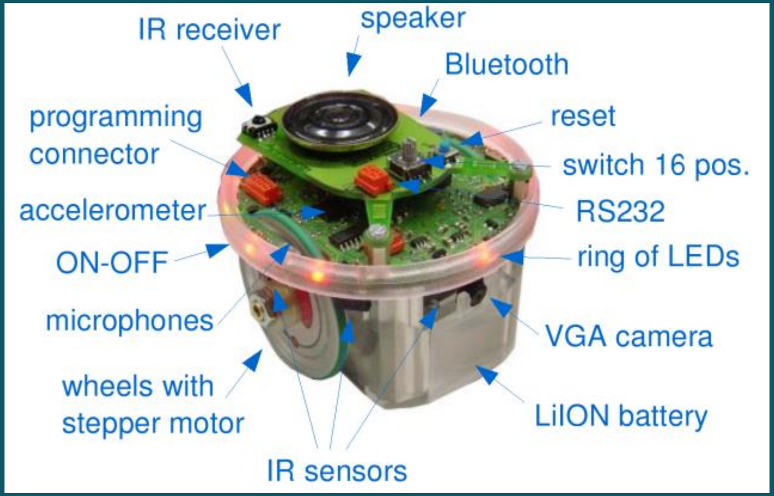
Work Accomplished

- Sensor research
- Communication protocol
- Software & hardware implementation
- Object detection/following

https://www.cyberbotics.com/item?id=8

Sensor Research

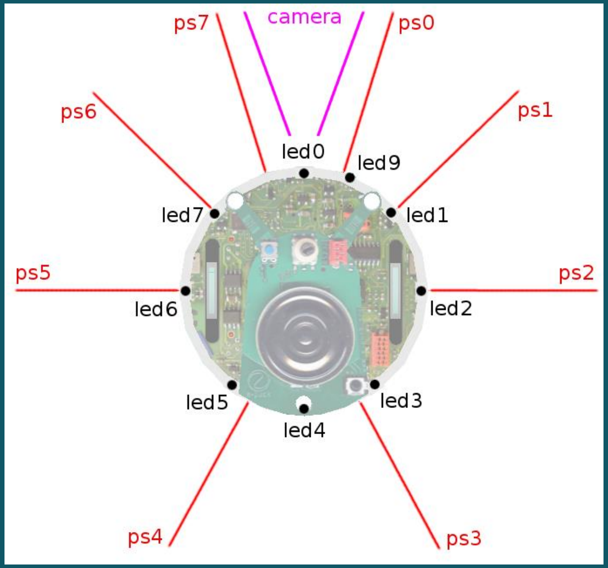
- Infrared receiver
  - Will be used to communicate with other robot platforms
- Distance measurement sensors
  - Used to detect and follow an object
  - Used for collision avoidance



http://www.generationrobots.com/en/401404-e-puck-programmable-robot-with-battery.html

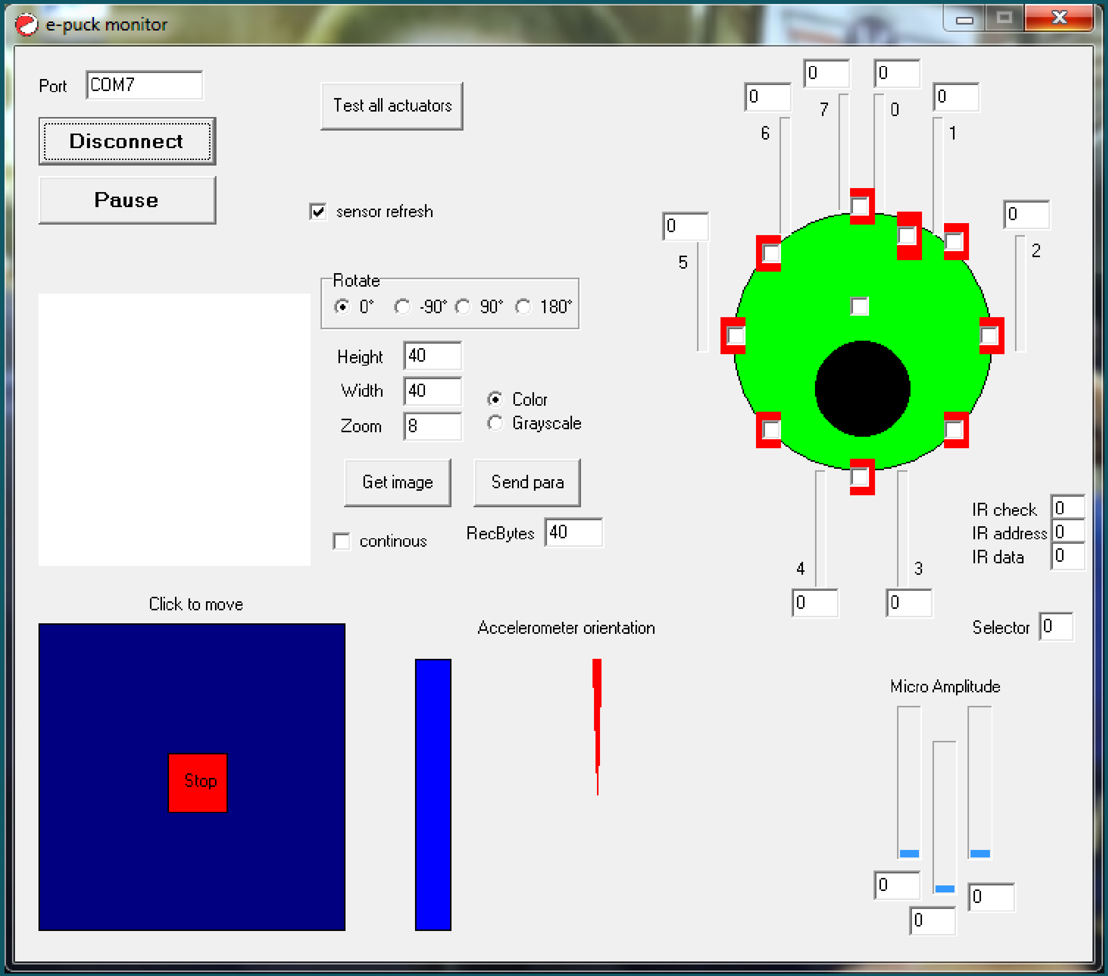
Infrared proximity sensors

- 8 infrared proximity sensors
  - Composed of two parts IR emitter & photo-sensor
- e_get_prox(int sensor_number)

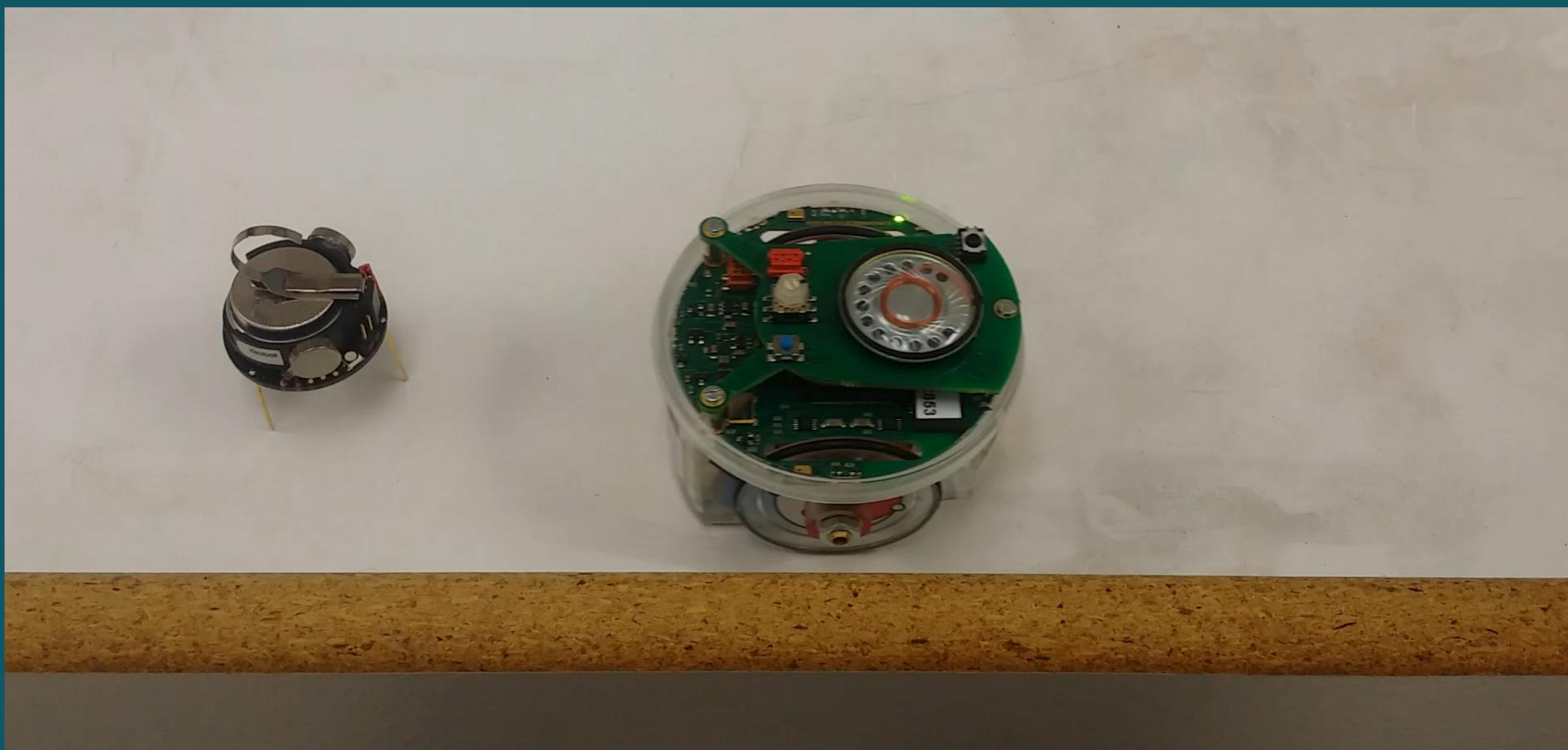


https://www.cyberbotics.com/guide/using-the-e-puck-robot.php

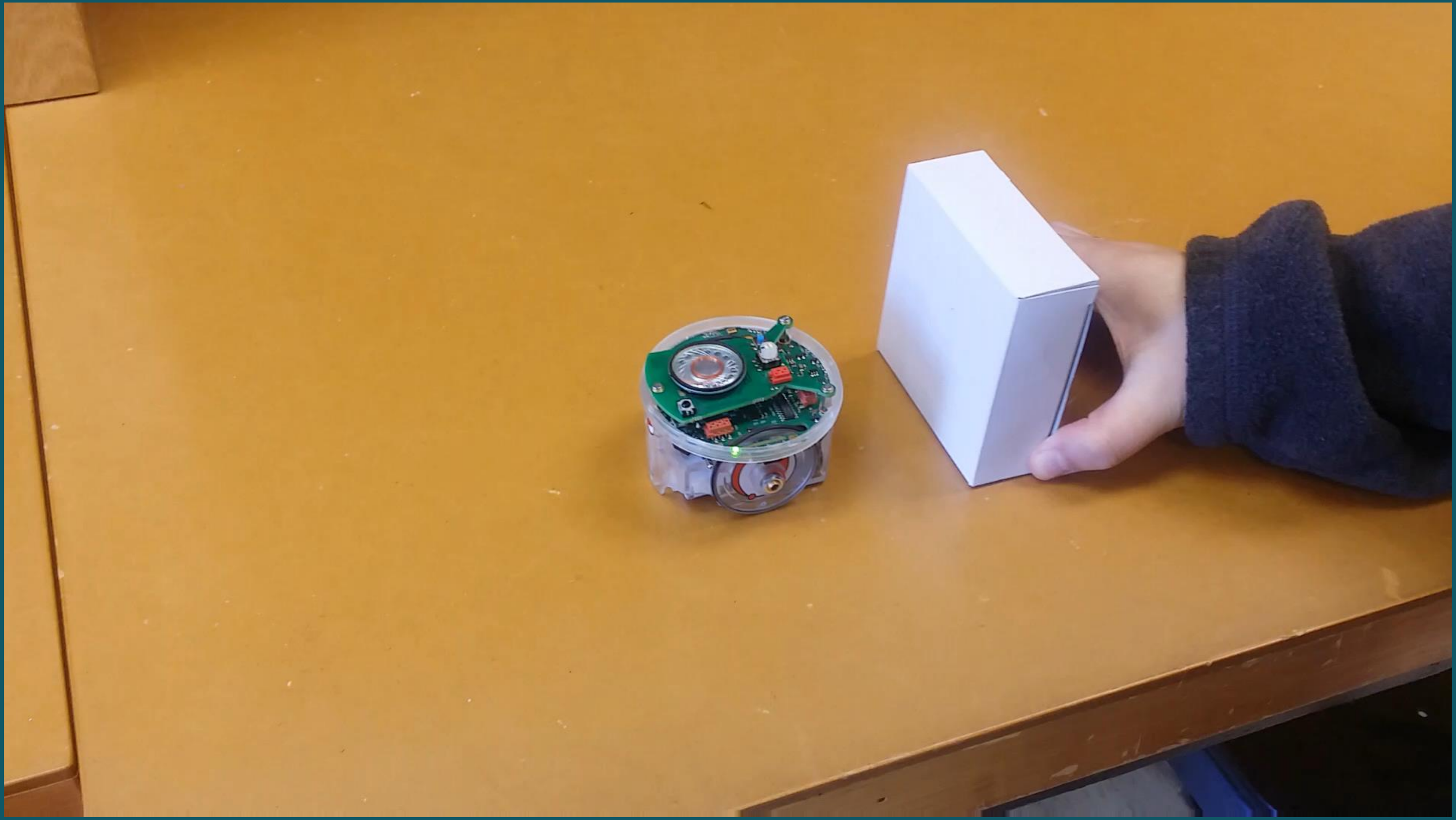
E-puck Monitor



Object Detection



Object Following



Problems Encountered

- Loss of battery life
- Infrared sensor communication
- Two disabled E-pucks
    - Using an ICD3 programmer to enable the E-pucks

http://www.microchip.com/Developmenttools/ProductDetails.aspx?PartNO=DV164035&utm_source=&utm_medium=MicroSolutions&utm_term=&utm_content=DevTools&utm_campaign=MPLAB+ICD+3+In-Circuit+Debugger

Future Work

- Continue to understand infrared communication
- E-puck to E-puck communication
- E-puck to Kilobot communication
- E-puck to Q-bot communication
- Enable 2 disabled E-pucks

Gantt Chart - Future Work

Task Name	Group Member Responsible for Task	Finish by Date	Nov-15		Dec-15					Jan-16				Feb-16		
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Research/Test E-puck - E-puck	Brittany	December 14, 2015														
Test Kilobot - E-puck	Jared/Brittany	December 14, 2015														
Test E-puck - Qbot	Brittany/Ryan/Greg	December 14, 2015														
Design Linear Based Model	All	December 14, 2015														
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Point Convergence	All	January 25, 2016														
Leader Follower	All	January 25, 2016														
Neighbor Repulsion	All	February 1, 2016														
Endpoint Attraction	All	February 1, 2016														
Heading	All	February 1, 2016														

Completed In progress

III. Kilobot Progress - Jared

Gantt Chart – Work Accomplished

Task Name	Group Member Responsible for Task	Finish by Date	Oct-15			Nov-15			
			13	20	27	3	10	17	24
Research/Test Kilobot - Kilobot	Jared	October 19, 2015							
Test Kilobot - E-puck	Jared/Brittany	December 14, 2015							
Test Kilobot - Qbot	Jared/Ryan/Greg	November 16, 2015							
Design Linear Based Model	All	December 14, 2015							
Localization	All	January 25, 2016							
Point Convergence	All	January 25, 2016							
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Endpoint Attraction	All	February 1, 2016							
Heading	All	February 1, 2016							

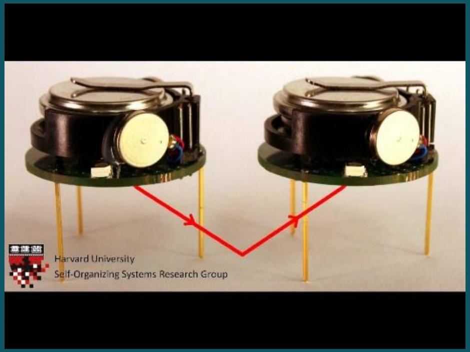
Completed In progress

Kilobot Communication

- 50% complete
- Successfully sent messages to Kilobots
- Currently implementing a receiver circuit

How Kilobots Communicate

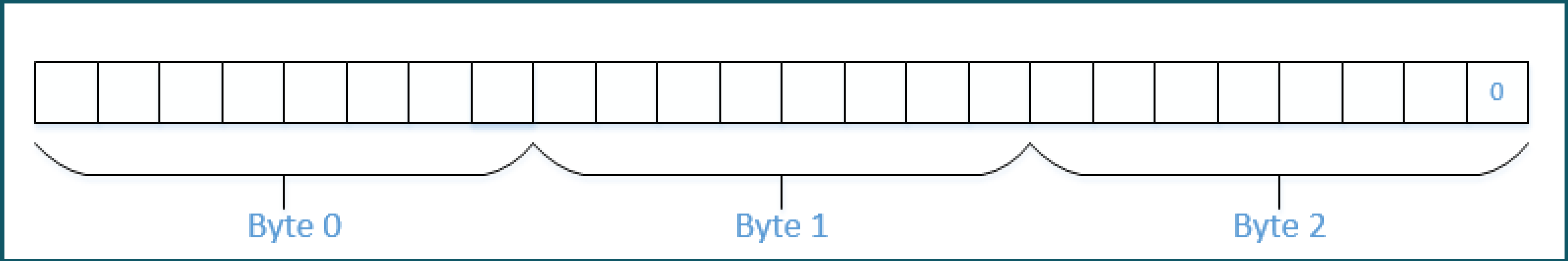
- Use infrared light
- Reflects light off the floor
- Measures light intensity to calculate distance
- Maximum rated range is 7 cm
- Messages are sent every 200 milliseconds



https://i.ytimg.com/vi/ISMwLCFwgK4/maxresdefault.jpg

Preparing Messages to send

- A message is composed of 23 bits (2 full characters, and an even character)
- A check sum is generated by taking the sum of the bits and 128
- All four bytes are operated on
- Each byte is then shifted left and incremented by 1

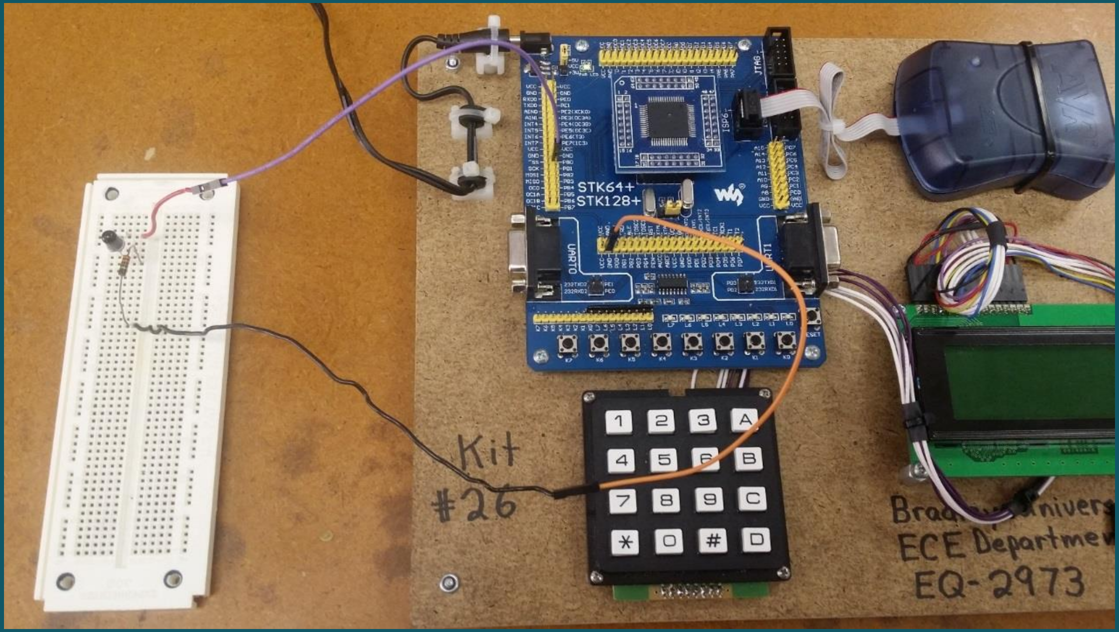


Sending messages

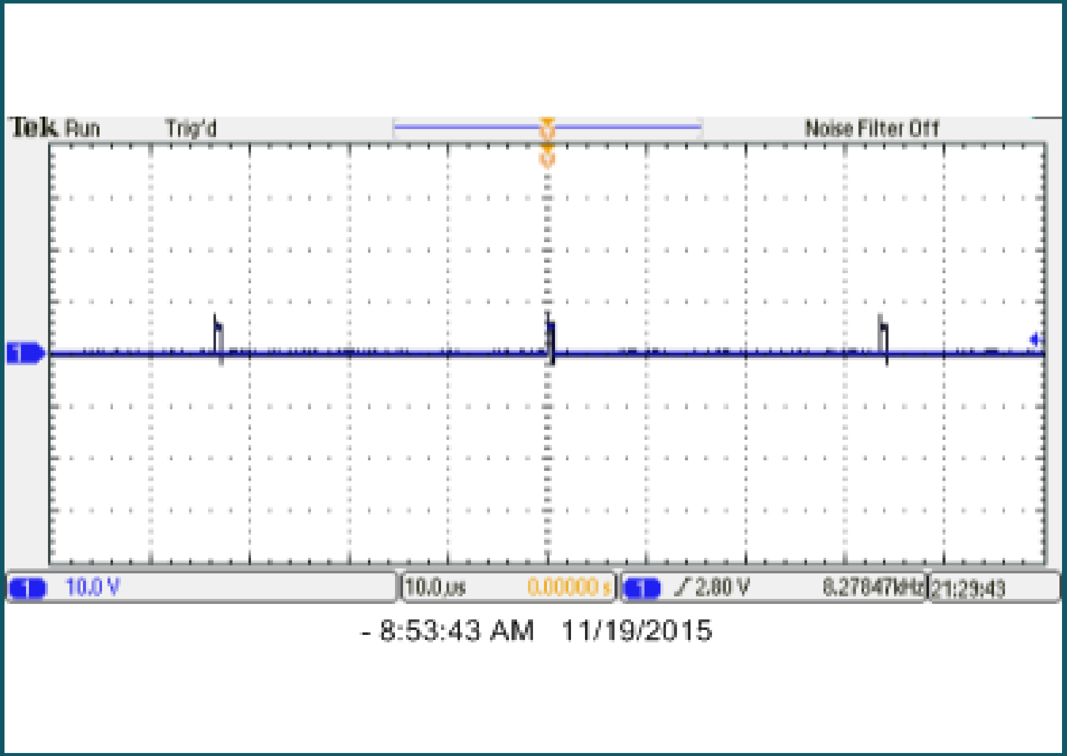
- Signal goes high briefly (0.75 microseconds)
- Signal is then set low for a duration (92.25 microseconds)
- Each bit is sent: high for 1, low for 0
- Signal is set low between each bit (13.875 microseconds per bit)
- 537 microseconds for entire message to be sent

Circuit

- Used an Atmega128 board from the lab
- PB0 in series with a 330 ohm resistor and an IR LED



Oscilloscope capture

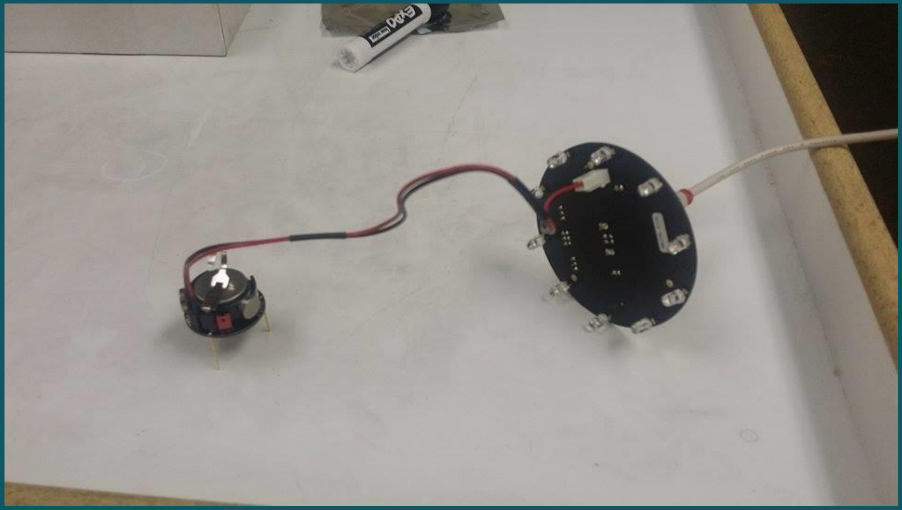


Initial Testing

- A Kilobot was programmed to turn its LED green if message was received
- The Kilobot turns it LED red if message is not received after a set amount of time
- The IR LED light was reflected off the ground next to the Kilobot

Further Testing

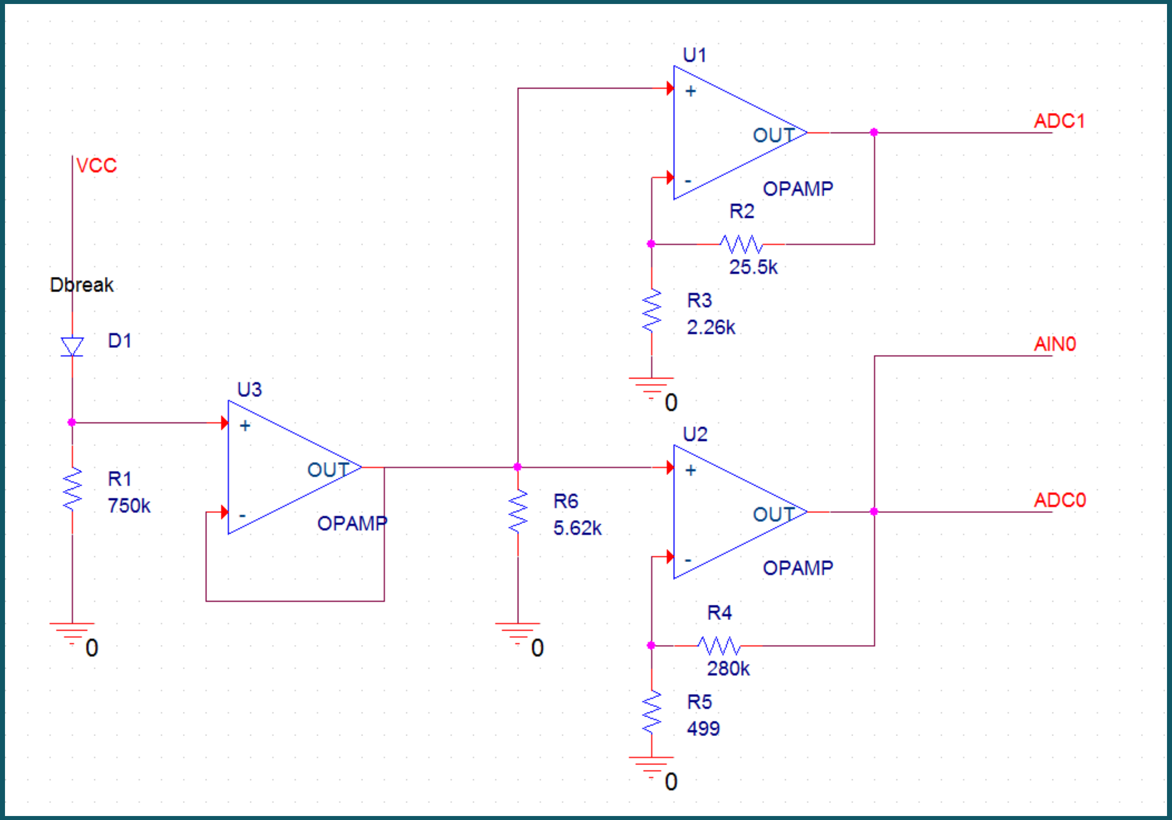
- Kilobot was connected to serial cable and programmed to print message values to hyper terminal
- Kilobot was placed at measured distances and compared to printed distance



Receiving messages

- Uses analog-to-digital conversion (ADC)
- Interrupt is triggered when IR receiver gets a pulse
- Uses the ADC gain to calculate distance

Receiver Circuit Diagram



Receiving circuit

- IR receiver is wired in series to the voltage source and resistors
- An op-amp is configured to a buffer and the + terminal is connected between the resistors and IR receiver
- The output of the buffer is then connected to two non-inverting configured op-amps
- The outputs of the two op-amps are then connected to the ADC channels on the microcontroller

Color Consensus

- Kilobots are initialized with a random number
- Each number corresponds to a color
- Kilobots then begin transmitting value
- Kilobots receive messages and keep track of how many neighbors are what color
- Kilobots then change their color to most prevalent color

Color Consensus Video

Localization

- Use a distributed Trilateration method
- Requires a minimum of 3 localized and non-collinear agents
- Agents initially assume a position of (0,0)
- Distances to localized Kilobots is known

Gantt Chart – Future Work

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Heading	All	February 1, 2016														

Completed In progress

III. Qbot2 Progress – Ryan & Greg

Qbot2 Progress - Ryan

Gantt Chart – Work Accomplished

Task Name	Group Member Responsible for Task	Finish by Date	Oct-15			Nov-15			
			13	20	27	3	10	17	24
Research Q-bot Communication Protocol	Ryan/Greg	October 19, 2015							
Research/Test Qbot - Qbot	Ryan/Greg	November 2, 2015							
Test Kilobot - Qbot	Jared/Ryan/Greg	November 16, 2015							
Test E-puck - Qbot	Brittany/Ryan/Greg	December 14, 2015							
Design Linear Based Model	All	December 14, 2015							
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Point Convergence	All	January 25, 2016							
Leader Follower	All	January 25, 2016							

Completed In progress

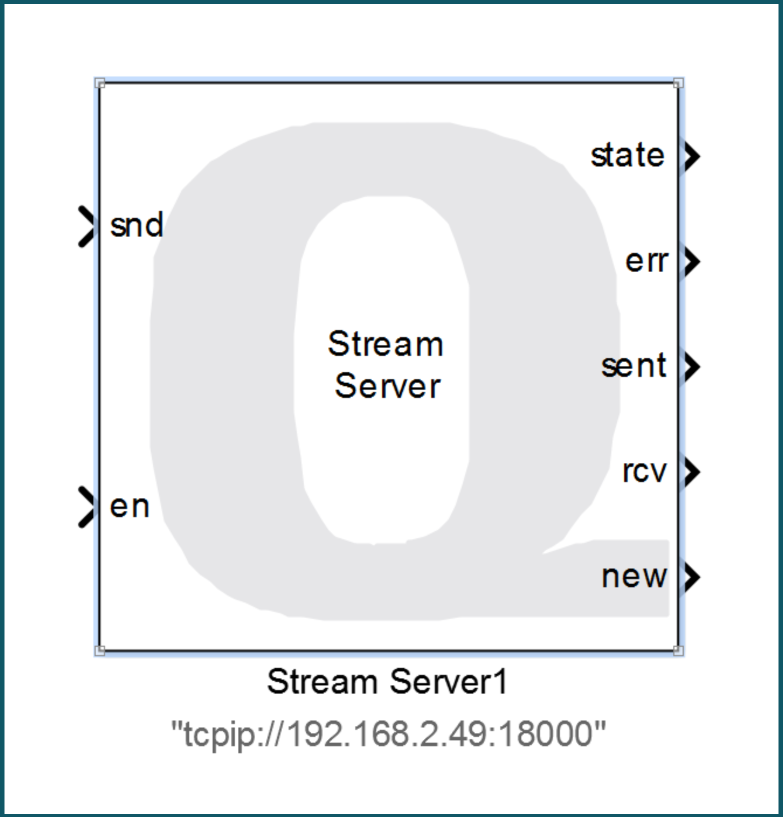
Qbot2 Progress

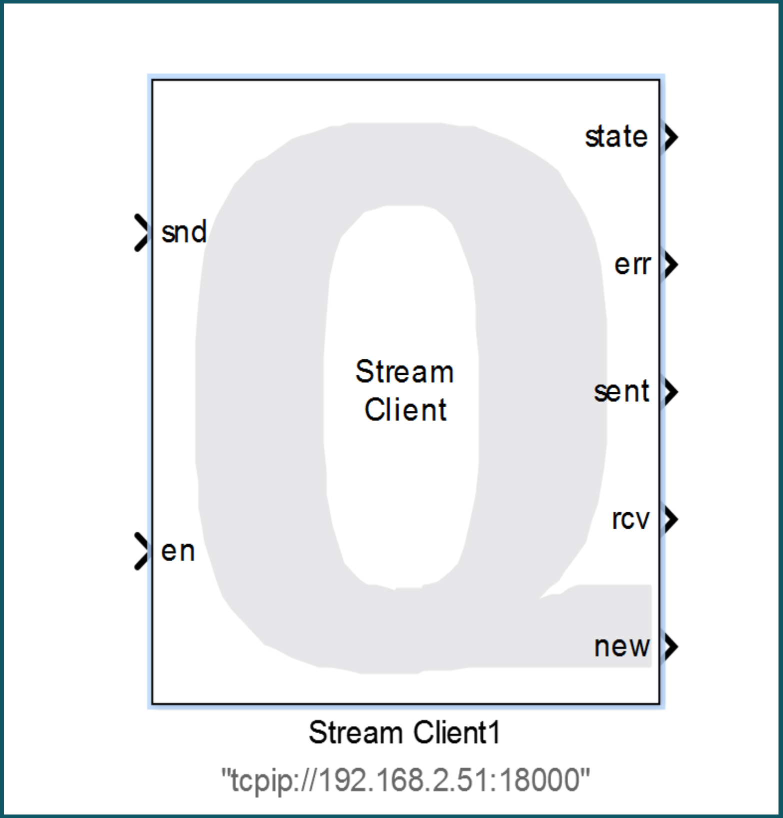
- Qbot-to-Qbot Communication
- Depth Sensing
- On-Board PWM

Qbot-to-Qbot Communication

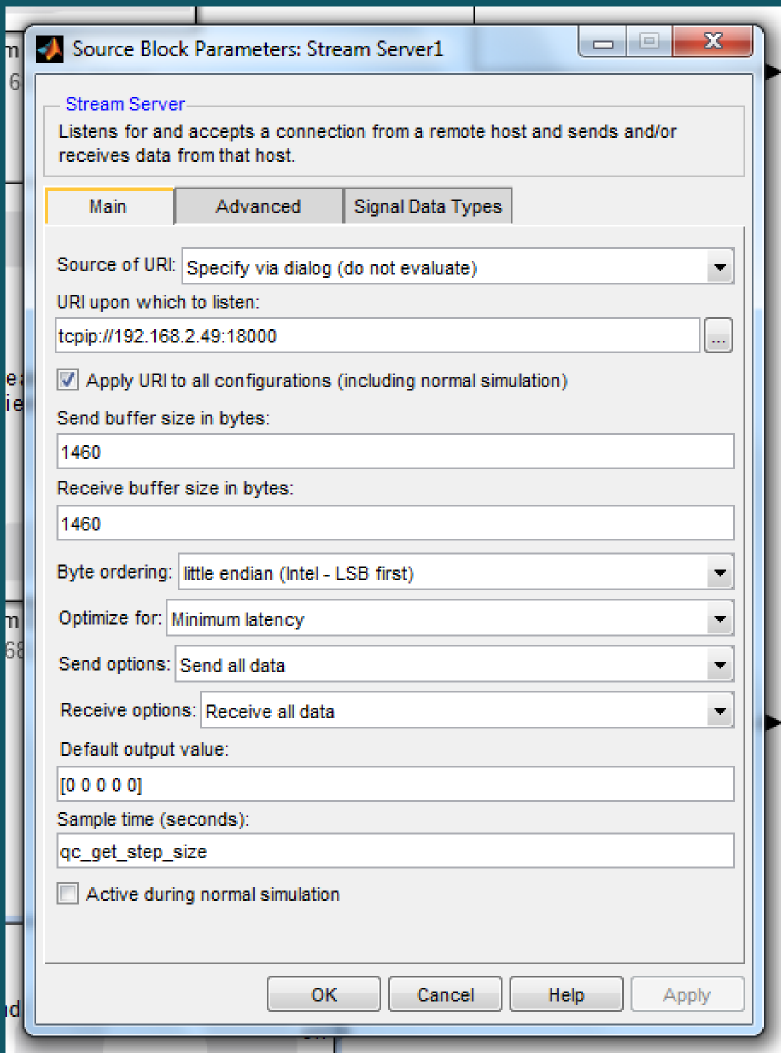
- Stream Server and Stream Client blocks
- Only one connection to block at a time
- Stays connected if MATLAB closes

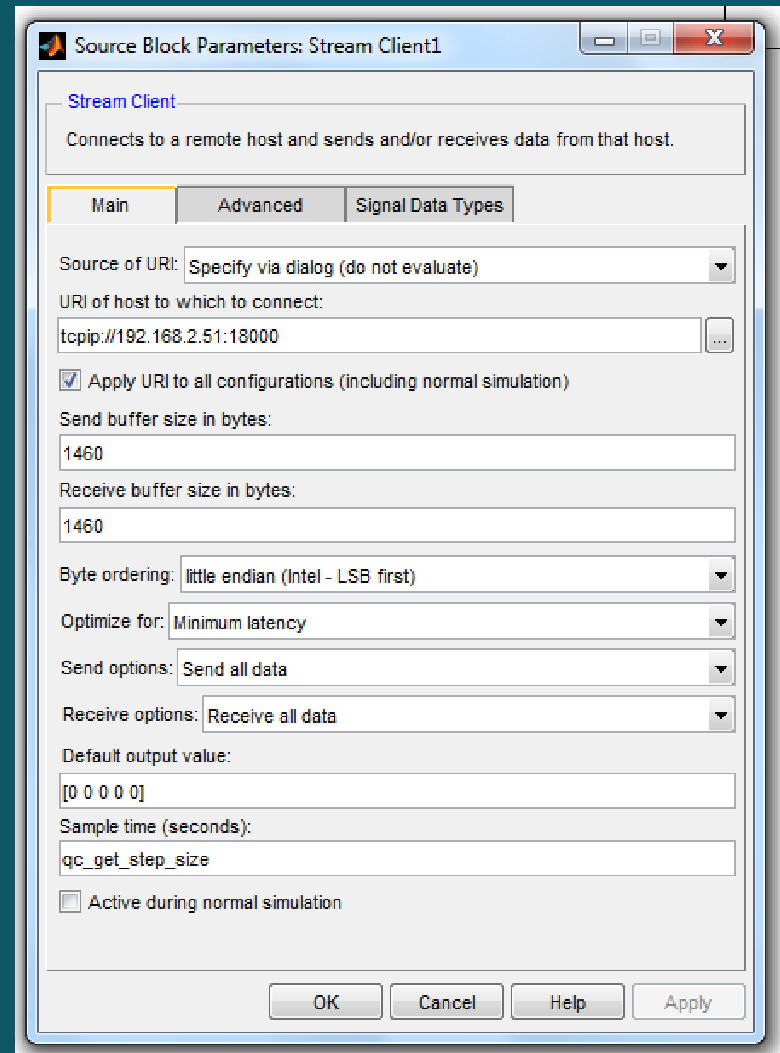
Stream Server and Stream Client





Stream Server and Stream Client





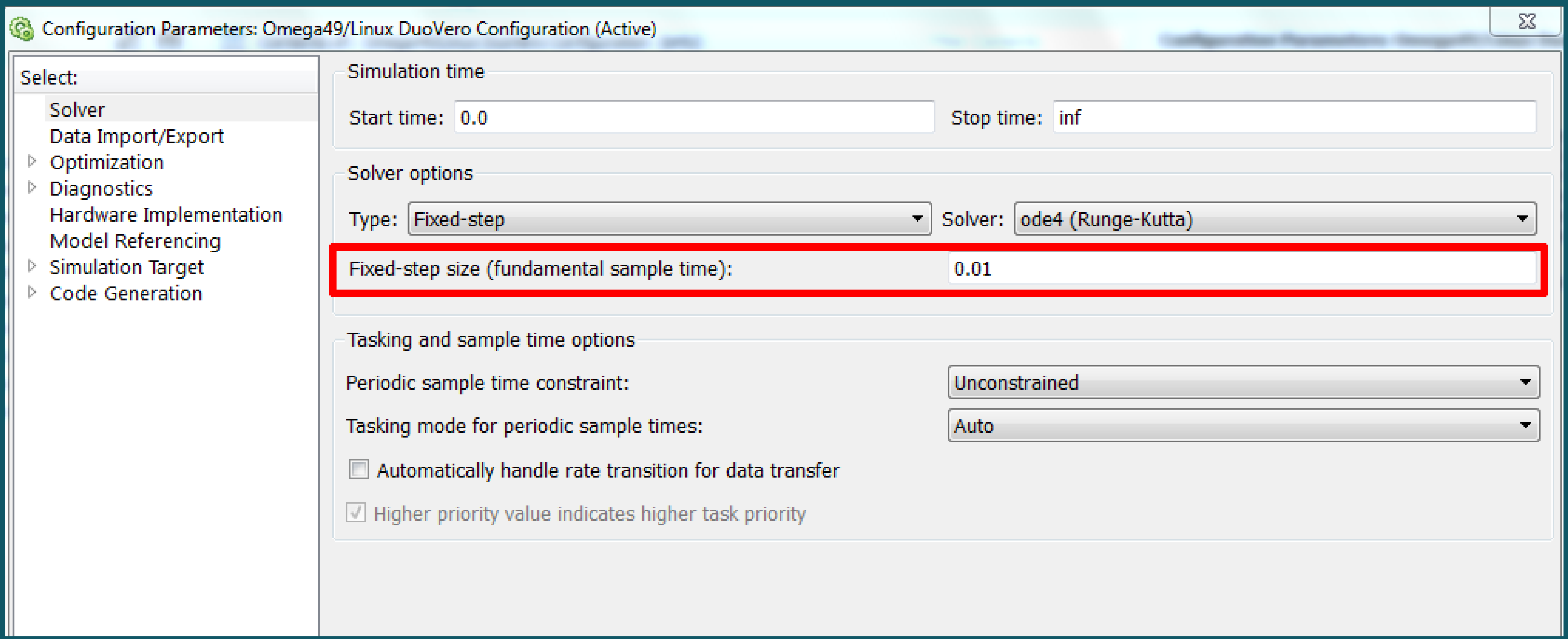
Depth Sensing

- Infrared (IR) Kinect Depth Sensor
- No more pixel count for distance
- Walls and other obstacles now can be avoided

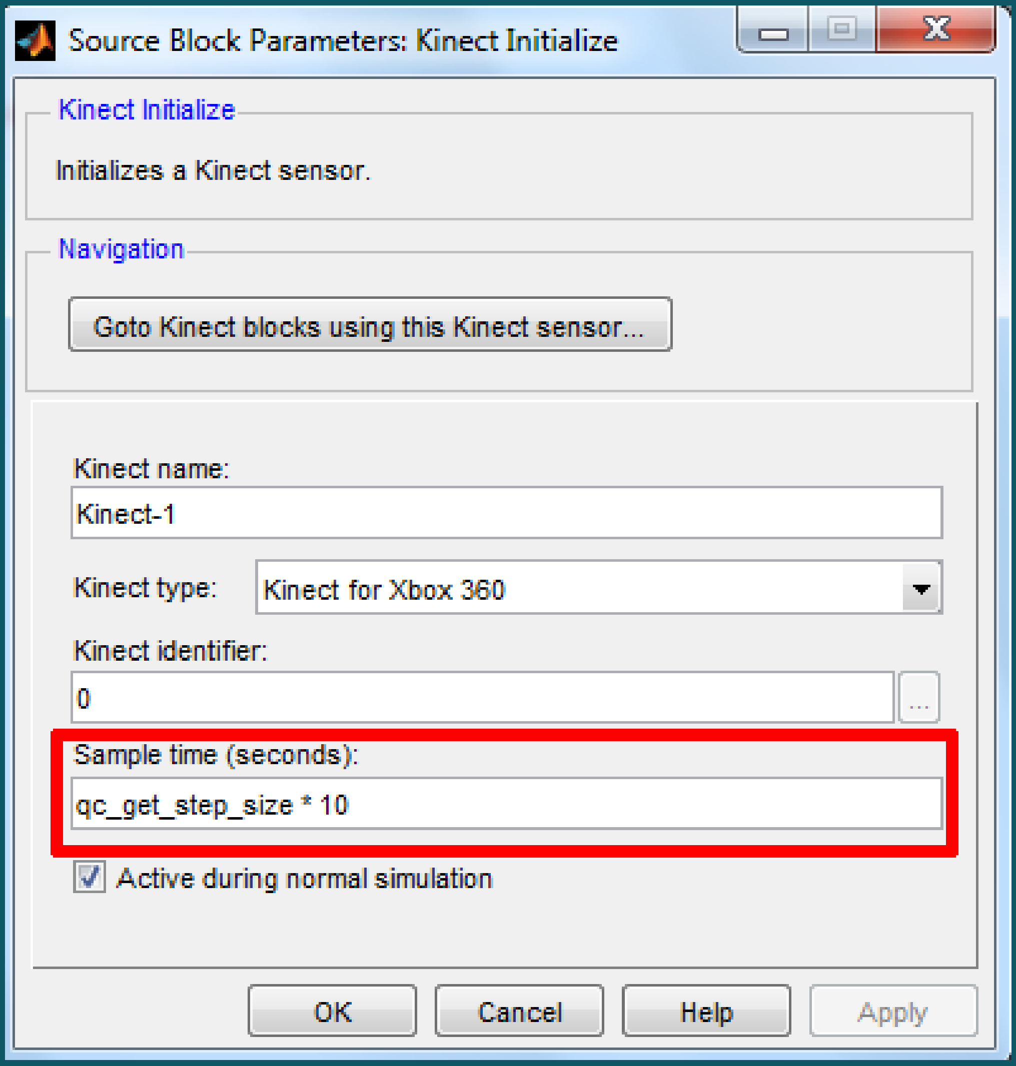
On-Board PWM

- Qbot clock of 1 gigahertz (GHz)
- Default sampling frequency of 100 hertz
- Simpler to use microcontroller

Sampling Time



Sampling Time



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Heading	All	February 1, 2016														

Completed In progress

Qbot2 Progress - Greg

Gantt Chart – Work Accomplished

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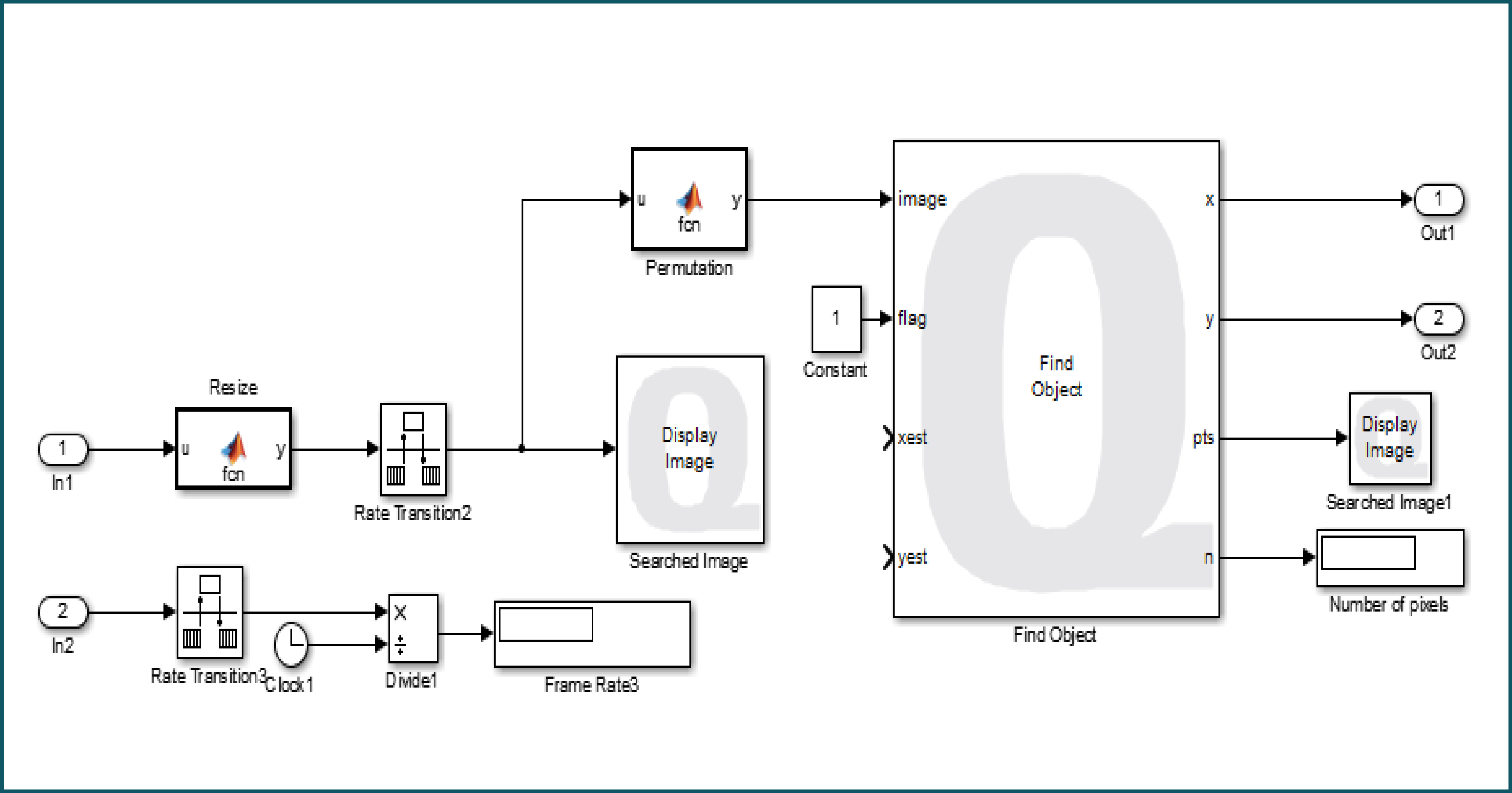
Formation Control Behavior									
Localization	All	January 25, 2016							
Point Convergence	All	January 25, 2016							
Leader Follower	All	January 25, 2016							

Completed In progress

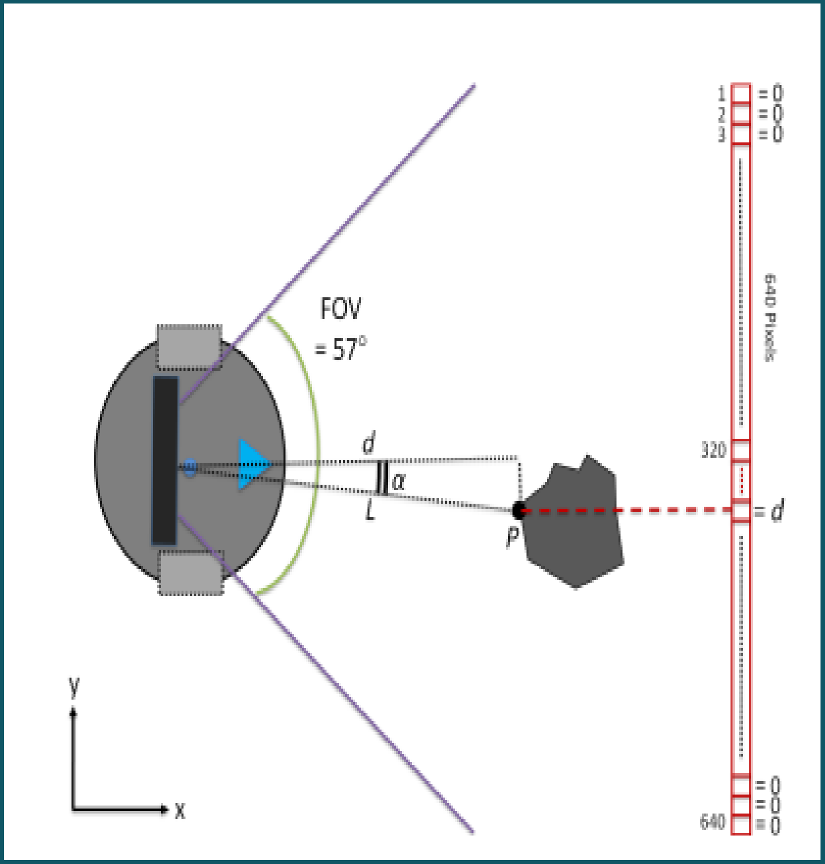
Localization

- Three main steps
  - Identify object
  - Determine depth and angle of object
  - Communicate calculated x and y values

Identify Object

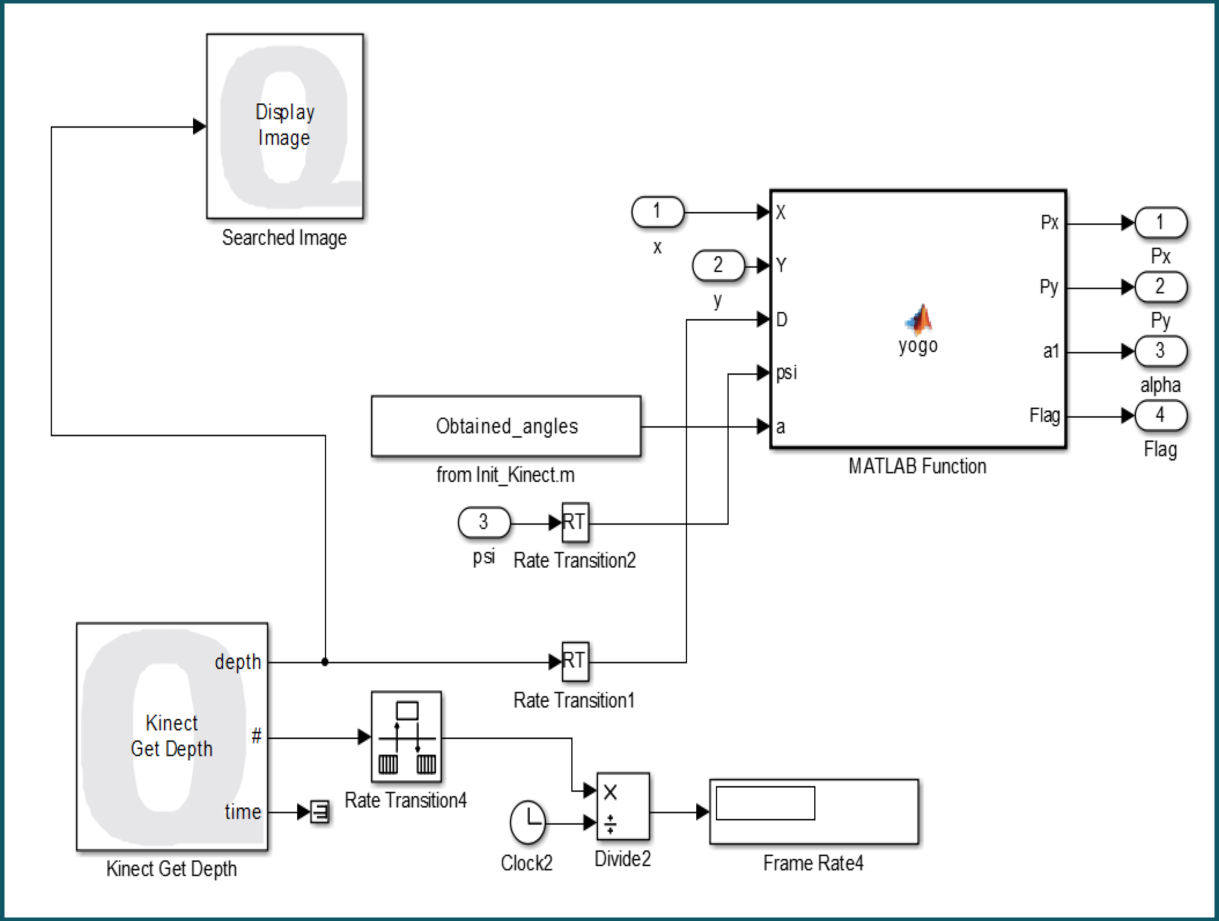


Determine Depth & Angle

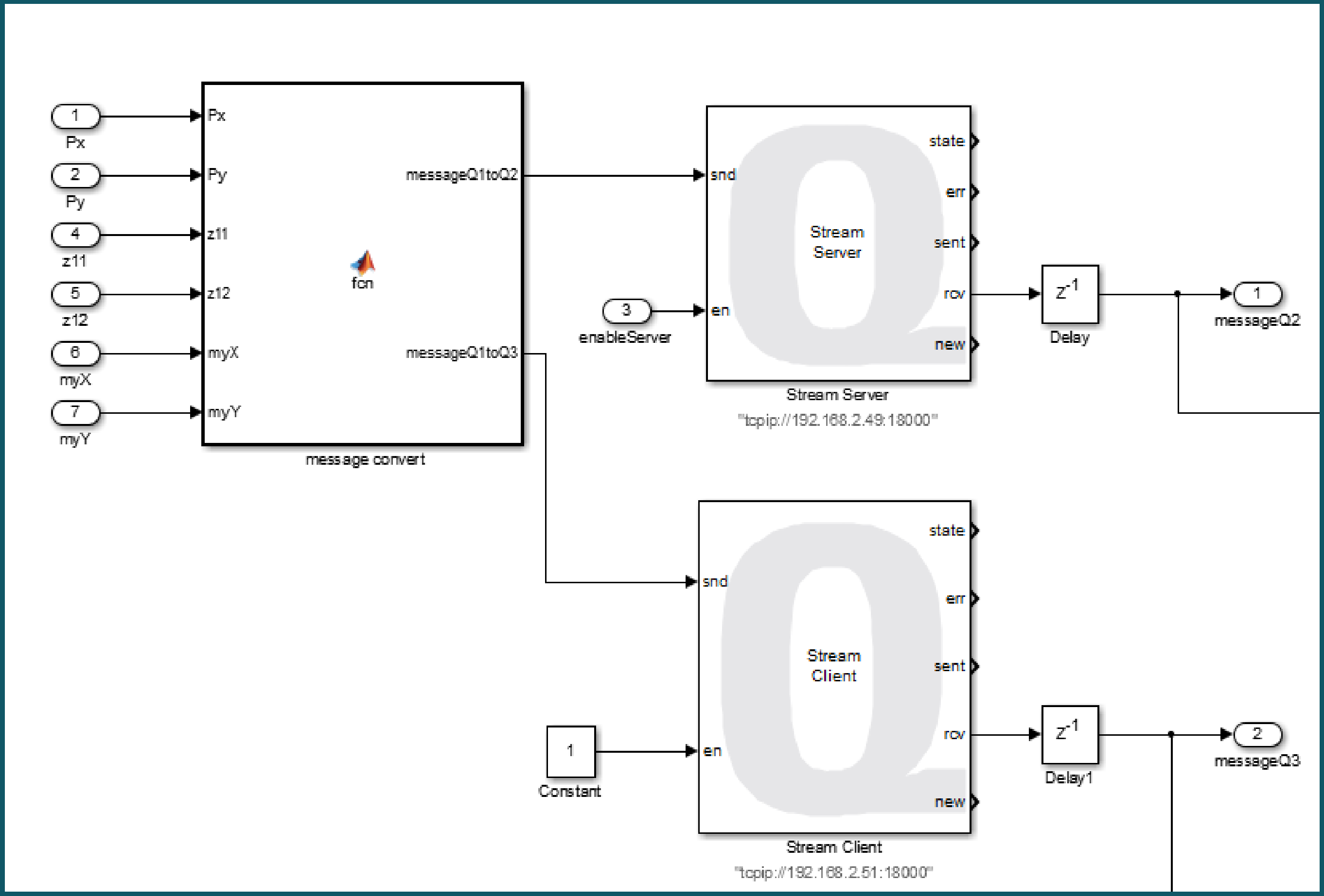


- Distance determined by depth sensor is the value d.
- $y = d \tan \alpha$

Determine Depth & Angle



Communicate Calculated Values



Point Convergence

- Qbots communicate localized coordinates
- Velocities are determined from the difference of communicating Qbots' coordinates

Point Convergence

- Equations
  - $V_{11} = K(Z_{21} - Z_{11})$
  - $V_{12} = K(Z_{22} - Z_{12})$
  - $V_{21} = K(Z_{31} - Z_{21})$
  - $V_{22} = K(Z_{32} - Z_{22})$
  - $V_{31} = K(Z_{11} - Z_{31})$
  - $V_{33} = K(Z_{12} - Z_{32})$

Point Convergence

- Equations
  - $Z_{n1} = x_n + d\cos\theta$
  - $Z_{n2} = y_n + d\sin\theta$
  - $Z'_{n1} = V\cos\theta - d\sin(\theta)\,\omega$
  - $Z'_{n2} = V\sin\theta + d\cos(\theta)\,\omega$
  - $\begin{bmatrix} V \\ \omega \end{bmatrix} = \begin{bmatrix} \cos\theta & -d\sin\theta \\ \sin\theta & d\cos\theta \end{bmatrix}^{-1} \begin{bmatrix} V_{n1} \\ V_{n2} \end{bmatrix}$

Point Convergence

Gantt Chart – Future Work

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Heading	All	February 1, 2016														

Completed In progress

VIII. Summary & Conclusions

Summary & Conclusions

- Design cooperative control algorithms for heterogeneous groups of robots
- Implement algorithms on different robot platforms
- Prevent collisions and implement network security
- Behind Schedule

Future Plan of Action

- Communication between platforms
- Algorithm design
- Integrated behavior

BRADLEY UNIVERSITY

COOPERATIVE CONTROL OF HETEROGENEOUS MOBILE ROBOTS NETWORK

Gregory Bock, Brittany Dhall, Ryan Hendrickson, & Jared Lamkin

Project Advisors: Dr. Jing Wang & Dr. In Soo Ahn

Department of Electrical and Computer Engineering

October 6th, 2015

Abbreviated Gantt Chart

Task Name	Target Dates	Sep-15					Oct-15				Nov-15				Dec-15					Jan-16				Feb-16				Mar-16				
		1	8	15	22	29	6	13	20	27	3	10	17	24	1	8	15	22	29	5	12	19	26	2	9	16	23	1	8	15	22	29
Individual Behavior	November 10, 2015																															
Individual Communication	December 14, 2015																															
Integrated Communication	December 14, 2015																															
Algorithm Design	December 14, 2015																															
Integrated Behavior	February 1, 2016																															
Testing	March 7, 2016																															

Complete Gantt Chart

Task Name	Group Member Responsible for Task	Finish by Date/Due Date	Sep-15					Oct-15				Nov-15				Dec-15					Jan-16				Feb-16				Mar-16					Apr-16			
			1	8	15	22	29	6	13	20	27	3	10	17	24	1	8	15	22	29	5	12	19	26	2	9	16	23	1	8	15	22	29	5	12	19	26
Individual Behavior																																					
Research Kilobot Sensors	Jared	September 28, 2015																																			
Research Kilobot Communication Protocol	Jared	October 12, 2015																																			
Research Q-bot Image Processing	Ryan/Greg	October 5, 2015																																			
Research Q-bot Sensors	Ryan/Greg	September 28, 2015																																			
Reseach Q-bot Communication Protocol	Ryan/Greg	October 19, 2015																																			
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Research E-puck Communication Protocol	Brittany																																				
Individual Communication																																					
Research/Test Kilobot - Kilobot	Jared	October 19, 2015																																			
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Heading	All	February 1, 2016																																			
Testing																																					
Software Implementation	All	March 7, 2016																																			
Hardware Implementation	All	March 7, 2016																																			

Deliverable Gantt Chart

Task Name	Group Member Responsible for Task	Finish by Date/Due Date	Sep-15					Oct-15				Nov-15				Dec-15					Jan-16				Feb-16				Mar-16					Apr-16			
			1	8	15	22	29	6	13	20	27	3	10	17	24	1	8	15	22	29	5	12	19	26	2	9	16	23	1	8	15	22	29	5	12	19	26
Deliverables																																					
Project Proposal - Oral Presentation	All	October 1, 2015																																			
Project Proposal - Document	All	October 15, 2015																																			
Webpage Release	All	October 28, 2015																																			
Fall Progress Presentation	All	November 19, 2015																																			
Fall Performance Evaluation	All	November 19, 2015																																			
Fall Performance Review	All	Decemeber 3, 2015																																			
Spring Progress Presentation	All	Feburary 18, 2016																																			
Student Expo Abstract	All	March 18, 2016																																			
Progject Demostration	All	March 24, 2016																																			
Final Presentation	All	April 7, 2016																																			
Student Expo Poster Printing Deadline	All	April 11, 2016																																			
Student Expo Poster Setup	All	April 12, 2016																																			
Sudent Expo	All	April 14, 2016																																			
Final Report (Draft)	All	April 14, 2016																																			
Final Report	All	April 28, 2016																																			
Final Web Page	All	April 28, 2016																																			
Advisory Board Poster Printing Deadline	All	April 28, 2016																																			
Advisory Board Poster Presentation	All	April 29, 2016																																			

Design Constraints

- Must overcome limited communication among networked robots
- Must overcome limited sensing capability of robots
- Must overcome system uncertainties

Objectives

- Mobile robot network should be applicable to different robot platforms
- Mobile robot network should be robust
- Mobile robot network should be autonomous

Solution

- Cooperative control algorithm design
  - Linear model
  - Non-linear model
- Deployment and validation through experimental testing
  - Modular design
  - System integration

Robot Model

- Linear Model
  - $\dot{x} = U_x$
  - $\dot{y} = U_y$
- Non-linear Model
  - $\dot{x} = vcos(\theta)$
  - $\dot{y} = vsin(\theta)$
  - $\dot{\theta} = \omega$

Solution Testing

- Software Implementation
  - Simulation
  - Algorithm validation
  - Algorithm implementation on platforms
- Hardware Implementation
  - Robot calibration
  - Multiple sensor fusion
- System Integration
  - Software
  - Hardware

Criteria to Determine a Successful Project

- Algorithm can be deployed on multiple robots
- Autonomous robots
- Communication amongst multiple robots

Project Funding

- Air Force Research Lab
- Air Force Proposal - "Multiagent task coordination using a distributed optimization approach”
- Grant Agreement Number – FA8780-13-1-0109

http://www.af.mil/News/Photos/tabid/129/igphoto/2000100887/Default.aspx

Expenses

- Robotic platforms (software included)
- Auxiliary components

Project Platform Costs

Platform	Quantity	Total Price
Qbot2	3	$9,999.00
Kilobot Kit	20	$4,583.00
Epucks	3	$5,093.00

Programming Software Costs

Software	Quantity	Total Price
Kilobot Controller IDE	1	$0.00
E-puck Programming Software	1	$0.00
MATLAB Courseware	1	$0.00

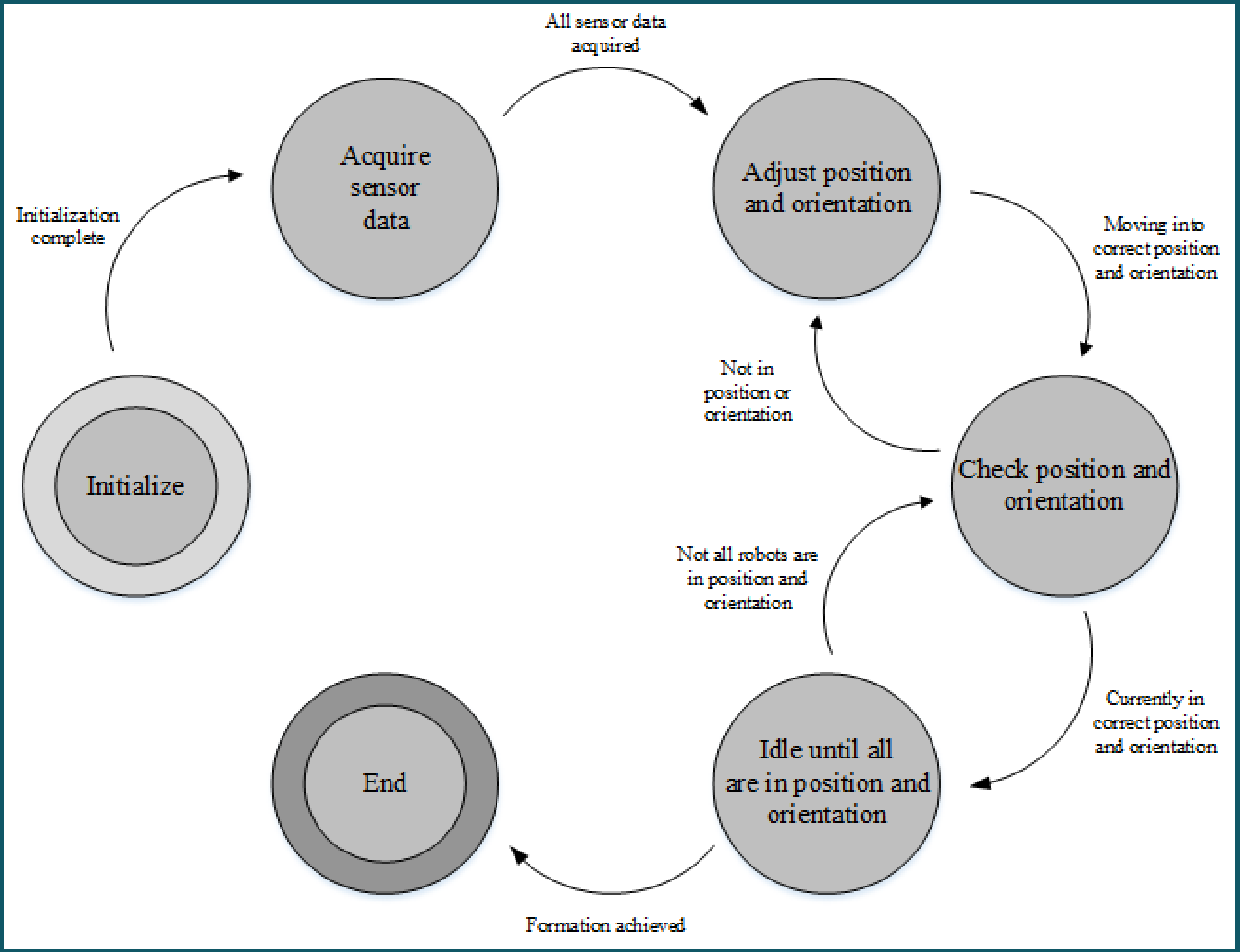
Gantt Chart

Task Name	Group Member Responsible for Task	Finish by Date	Sep-15					Oct-15				Nov-15				Dec-15					Jan-16				Feb-16				Mar-16					Apr-16			
			1	8	15	22	29	6	13	20	27	3	10	17	24	1	8	15	22	29	5	12	19	26	2	9	16	23	1	8	15	22	29	5	12	19	26
Individual Behavior																																					
Research Kilobot Sensors	Jared	September 28, 2015																																			
Research Kilobot Communication Protocol	Jared	October 12, 2015																																			
Research Q-bot Image Processing	Ryan/Greg	October 5, 2015																																			
Research Q-bot Sensors	Ryan/Greg	September 28, 2015																																			
Research Q-bot Communication Protocol	Ryan/Greg	October 19, 2015																																			
Research E-puck Sensors	Brittany	October 26, 2015																																			
Research E-puck Communication Protocol	Brittany																																				
Individual Communication																																					
Research/Test Kilobot - Kilobot	Jared	October 19, 2015																																			
Research/Test E-puck - E-puck	Brittany	December 14, 2015																																			
Research/Test Qbot - Qbot	Ryan/Greg	November 2, 2015																																			
Integrated Communication																																					
Test Kilobot - E-puck	Jared/Brittany	December 14, 2015																																			
Test Kilobot - Qbot	Jared/Ryan/Greg	November 16, 2015																																			
Test E-puck - Qbot	Brittany/Ryan/Greg	December 14, 2015																																			
Algorithm Design																																					
Design Linear Based Model	All	December 14, 2015																																			
Integrated Behavior																																					
Formation Control Behavior																																					
Localization	All	January 25, 2016																																			
Point Convergence	All	January 25, 2016																																			
Leader Follower	All	January 25, 2016																																			
Flocking Behavior																																					
Neighbor Repulsion	All	February 1, 2016																																			
Endpoint Attraction	All	February 1, 2016																																			
Heading	All	February 1, 2016																																			
Testing																																					
Software Implementation	All	March 7, 2016																																			
Hardware Implementation	All	March 7, 2016																																			

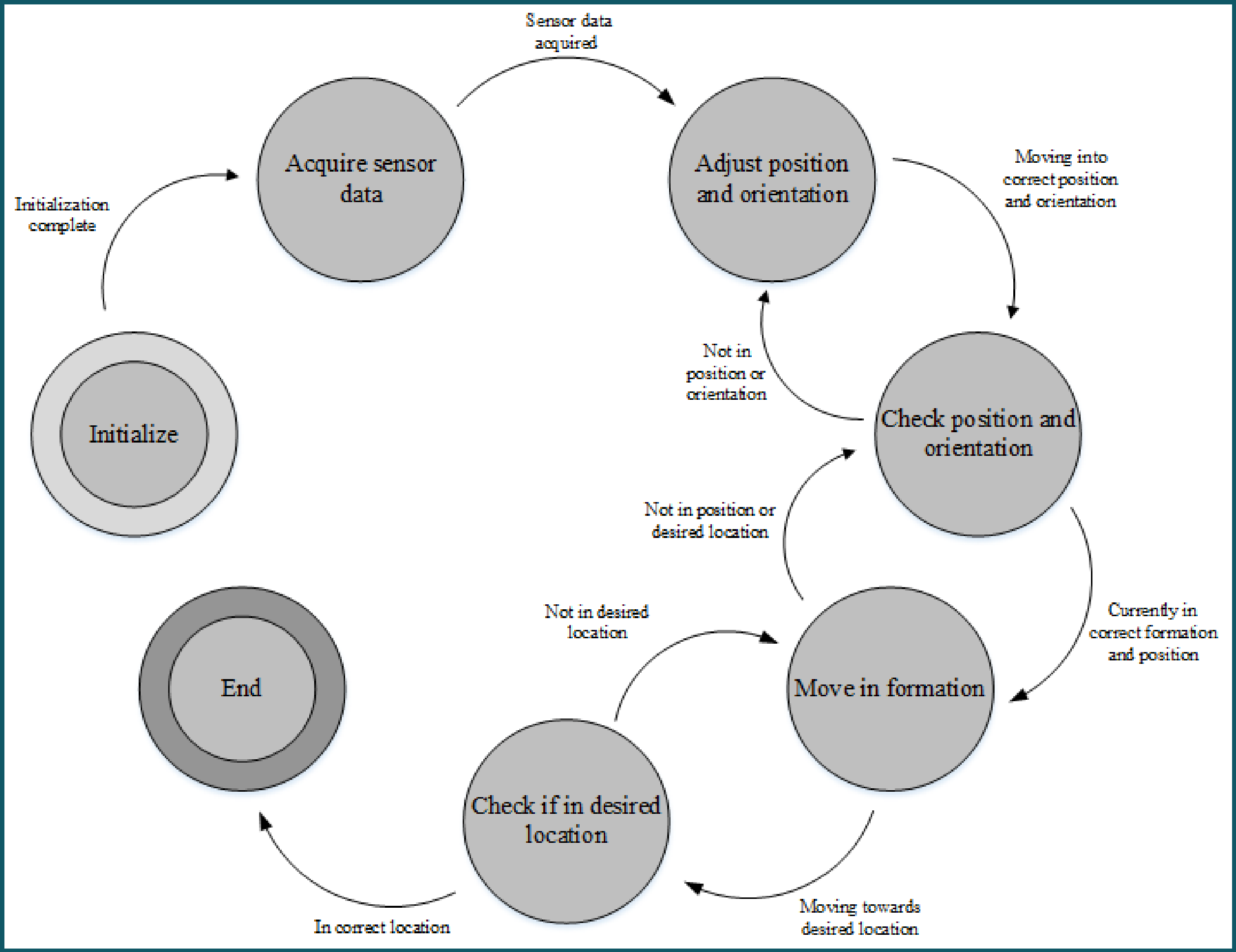
Gantt Chart – Deliverables

Task Name	**Finish by Date/Due Date**	**Sep-15**					**Oct-15**				**Nov-15**				**Dec-15**					**Jan-16**				**Feb-16**				**Mar-16**					**Apr-16**			
		1	8	15	22	29	6	13	20	27	3	10	17	24	1	8	15	22	29	5	12	19	26	2	9	16	23	1	8	15	22	29	5	12	19	26
Deliverables																																				
Project Proposal - Oral Presentation	October 1, 2015																																			
Project Proposal - Document	October 15, 2015																																			
Webpage Release	October 28, 2015																																			
Fall Progress Presentation	November 19, 2015																																			
Fall Performance Evaluation	November 19, 2015																																			
Fall Performance Review	December 3, 2015																																			
Spring Progress Presentation	February 18, 2016																																			
Student Expo Abstract	March 18, 2016																																			
Project Demonstration	March 24, 2016																																			
Final Presentation	April 7, 2016																																			
Student Expo Poster Printing Deadline	April 11, 2016																																			
Student Expo Poster Setup	April 12, 2016																																			
Student Expo	April 14, 2016																																			
Final Report (Draft)	April 14, 2016																																			
Final Report	April 28, 2016																																			
Final Web Page	April 28, 2016																																			
Advisory Board Poster Printing Deadline	April 28, 2016																																			
Advisory Board Poster Presentation	April 29, 2016																																			

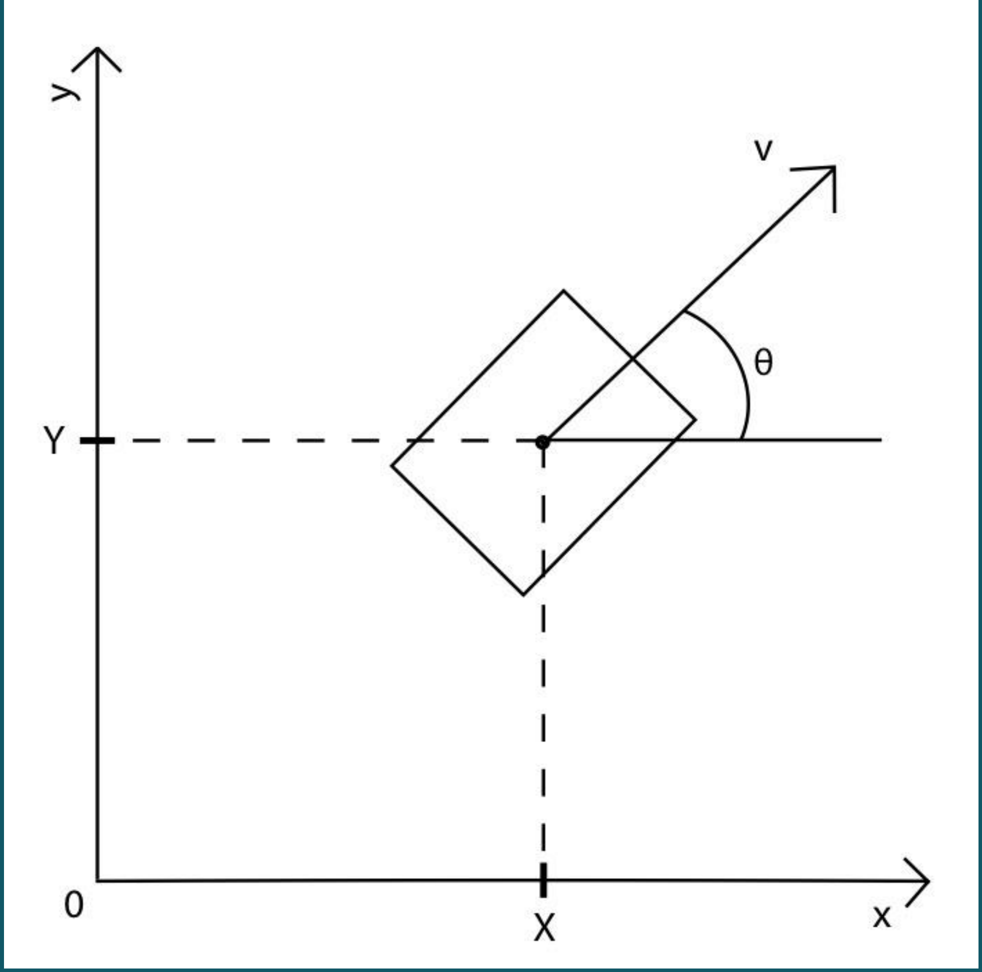
State Diagram: Formation Control Behavior



State Diagram: Flocking Formation

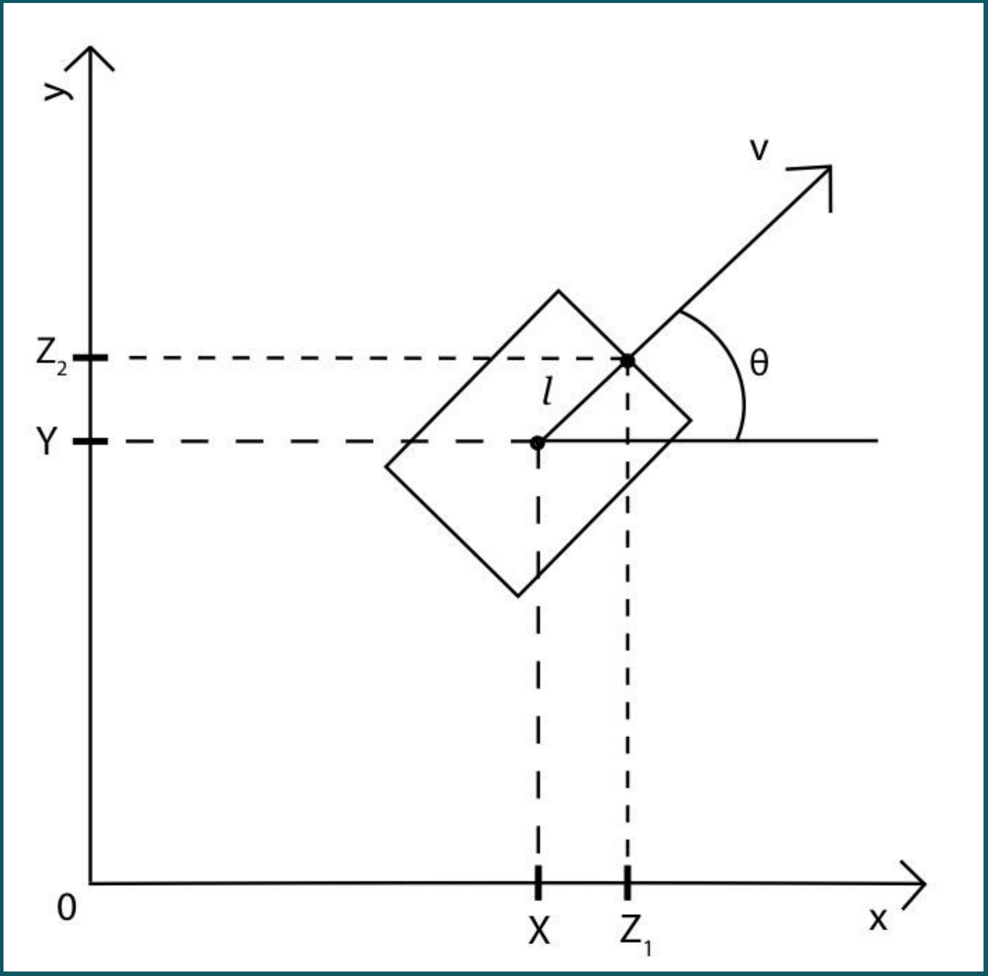


Non-linear Model



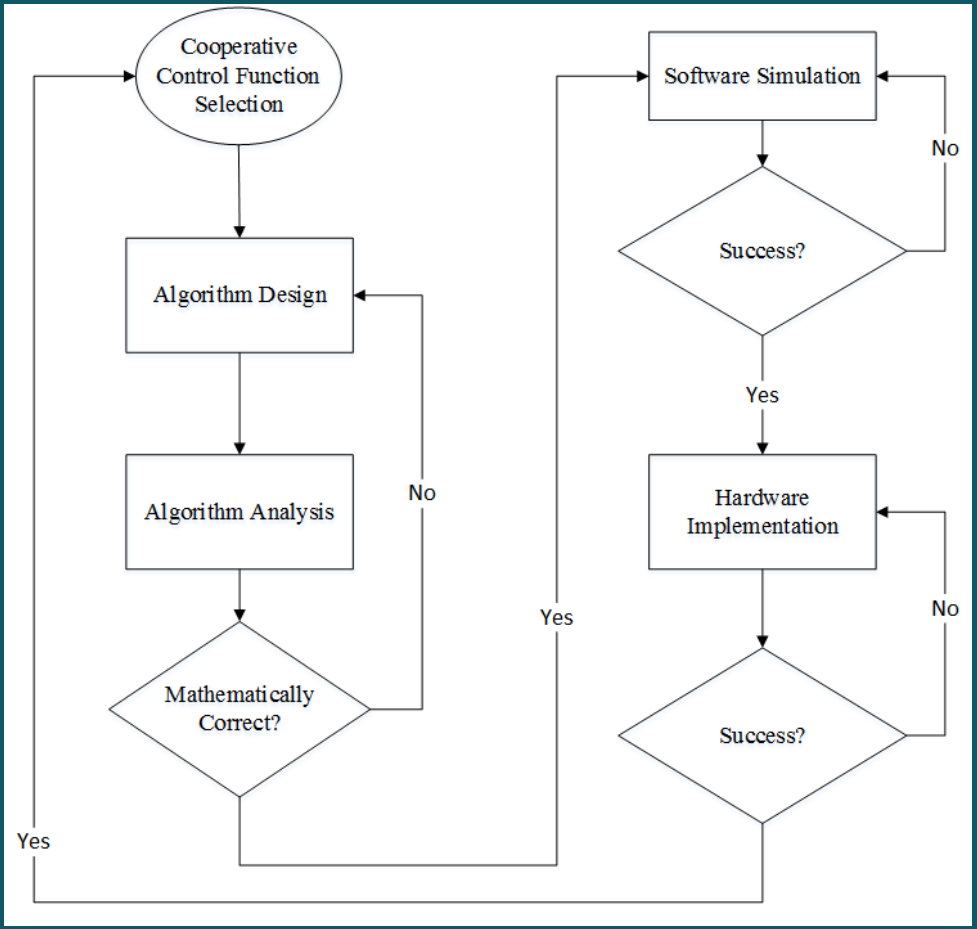
Quanser Inc. “QBOT 2 Workbook” Markham, Ontario

Linear Model



Quanser Inc. “QBOT 2 Workbook” Markham, Ontario

Solution Testing



E-puck Object Following Code

```
/***********************************************************************/
/** Motor speed controlled depending on front proximity sensor values **/
/***********************************************************************/

#include "p30f6014A.h"
#include "e_epuck_ports.h"
#include "e_init_port.h"
#include "e_ad_conv.h"
#include "e_prox.h"
#include "e_motors.h"

#define DELAY 50000

int main() {

    long timer = 0;

    //system initialization
    e_init_port();              // configure port pins
    e_init_ad_scan(ALL_ADC);    // configure Analog-to-Digital Converter Module

    while (1) {

        if (e_get_prox(0)> 500) {       //escape
            e_set_speed_left(0);
            e_set_speed_right(0);
        } else if (e_get_prox(0)>100) { //follow
            e_set_speed_left(400);
            e_set_speed_right(400);
        } else {                        //stop
            e_set_speed_left(0);
            e_set_speed_right(0);
        }

        //wait a little to let the robot move
        for(timer = 0; timer < DELAY; timer++);

    }
}
```

Kilobot message operations

```
data_out[i]=(data_to_send[i] & (1<<0))*128 +
(data_to_send[i] & (1<<1))*32 +
(data_to_send[i] & (1<<2))*8 +
(data_to_send[i] & (1<<3))*2+
(data_to_send[i] & (1<<4))/2+
(data_to_send[i] & (1<<5))/8 +
(data_to_send[i] & (1<<6))/32 +
(data_to_send[i] & (1<<7))/128;

data_out[i]=data_out[i]<<1;
data_out[i]++;
```

LEDs and Buttons

- Found LED and Button addresses for reading and writing
- LEDs can be used for debugging
- Buttons can be used for synchronous start-up

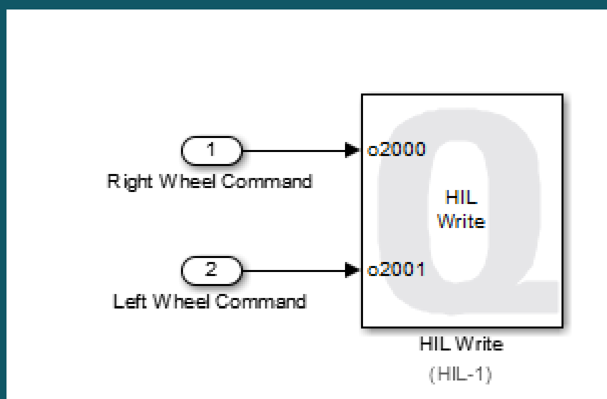
QBot Point Convergence Code

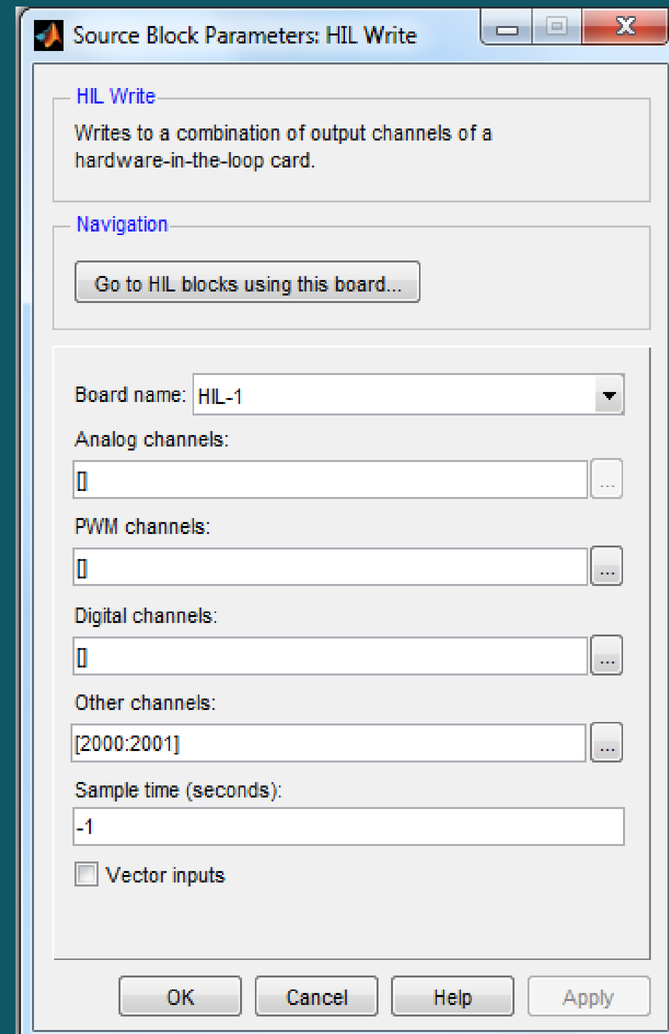
```
v11 = k1*(z21 - z11); % Calculate velocity in x direction
v12 = k2*(z22 - z12); % Calculate velocity in y direction
mat = [cos(myTheta) -d/2*sin(myTheta); sin(myTheta) d/2*cos(myTheta)];
myControl = inv(mat)*[v11;v12];

% Determine total velocity
V = myControl(1);

% Determine angular velocity
omega = myControl(2);

% Determine left and right wheel velocity
Vl = (2*V-d*omega)/2;
Vr = (2*V+d*omega)/2;
```

QBot Obtained Angle Equation

- $\alpha = (320\ - column) * (57/640) * (\pi - 180)$

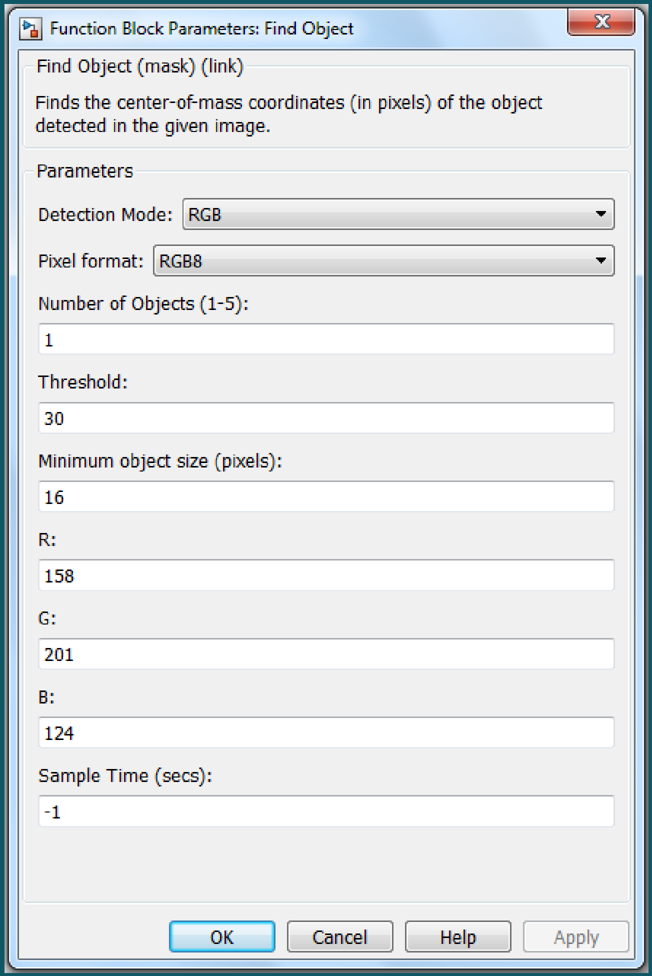
HIL Write Block



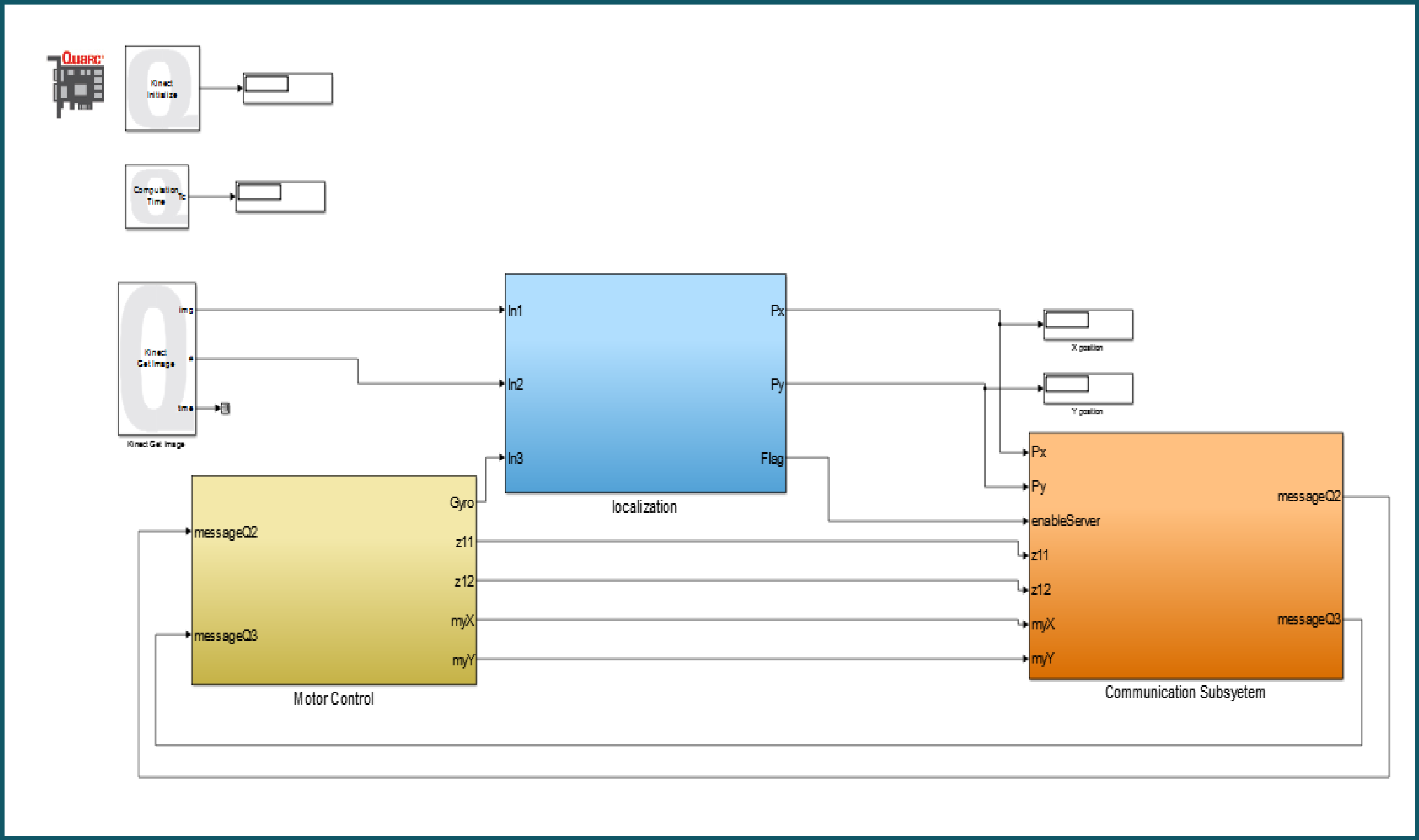


Find Object Parameters

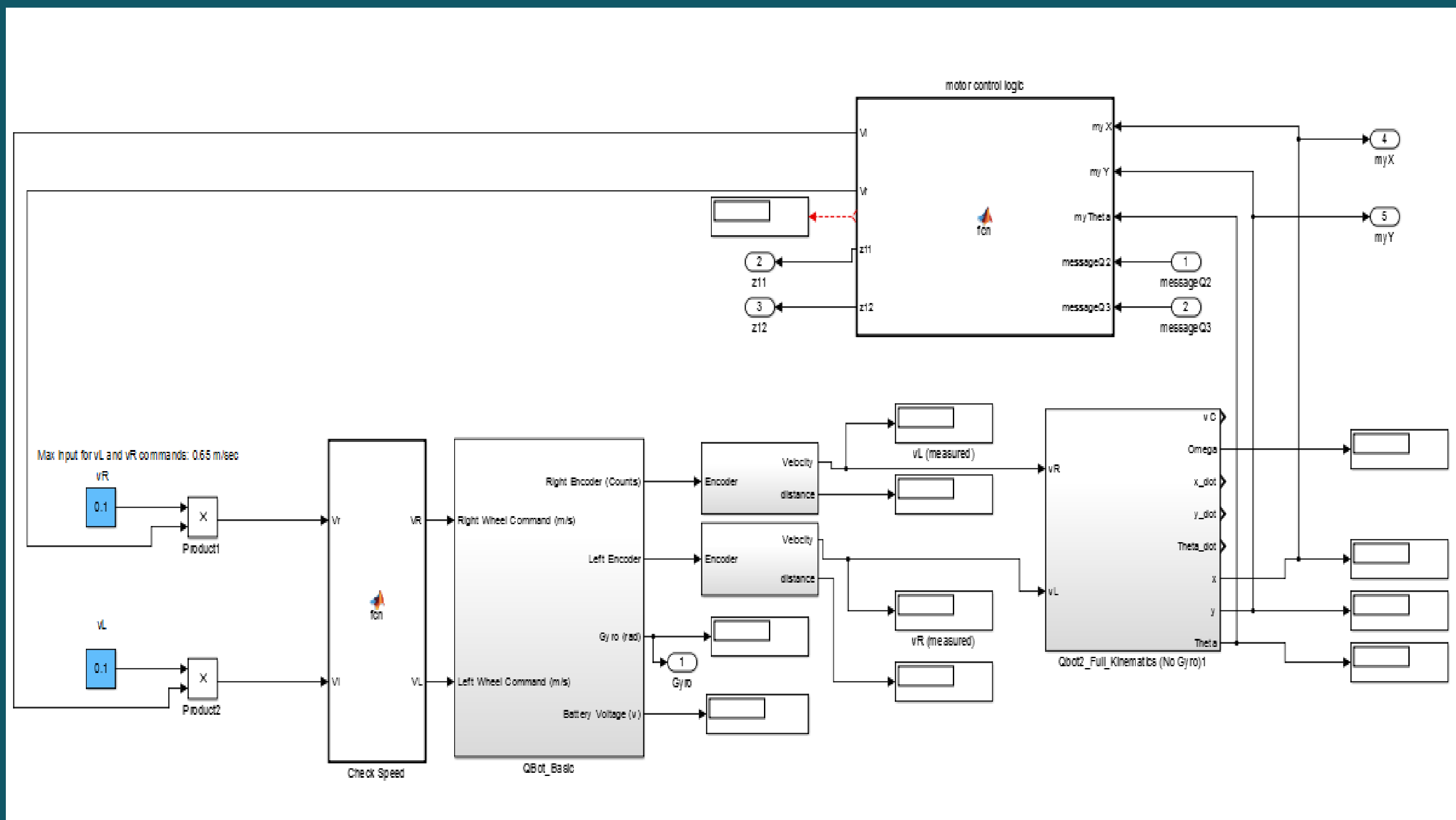
- Specify RGB values
- Value threshold
- Number of objects



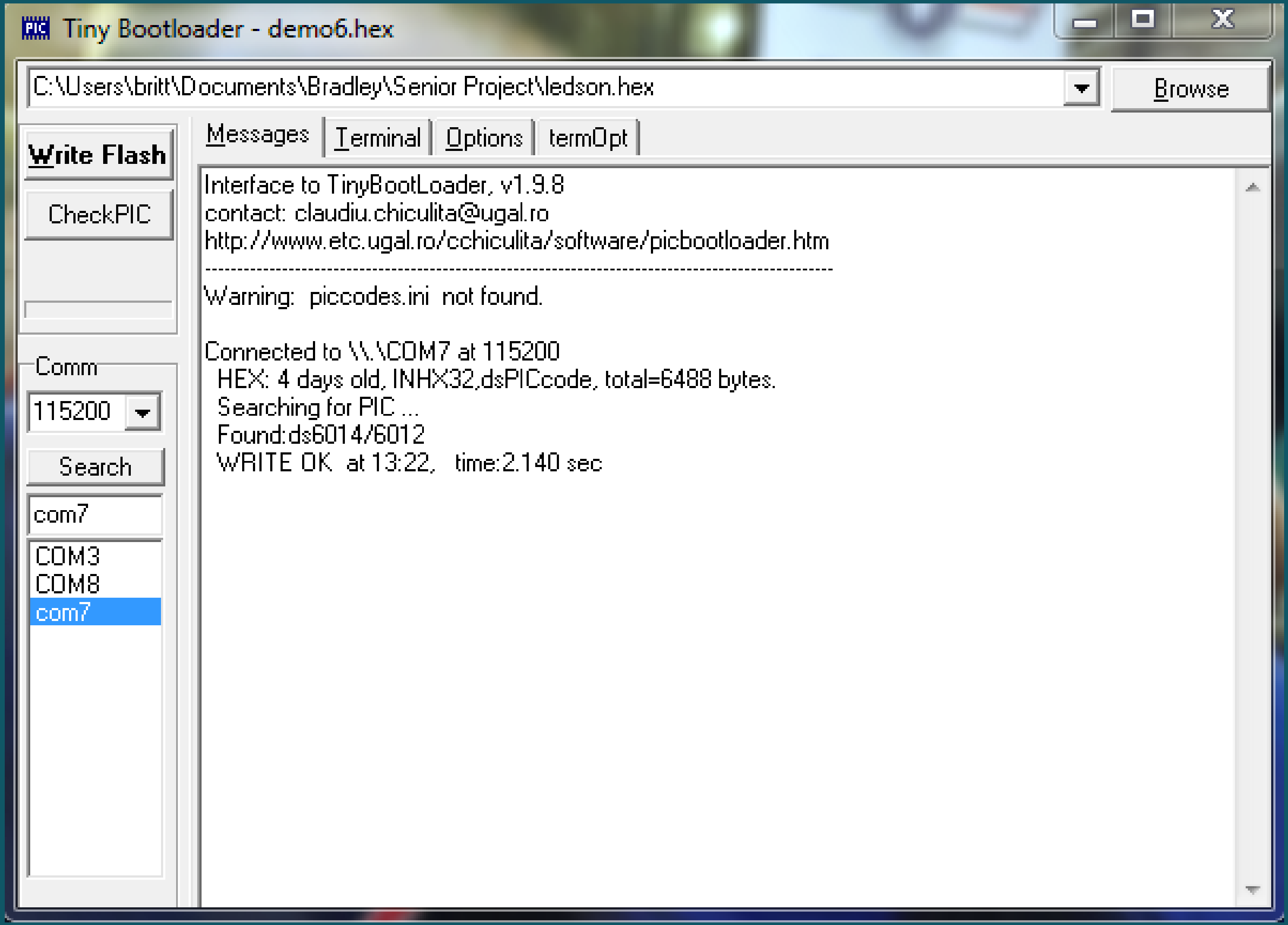
Overall Simulink Model



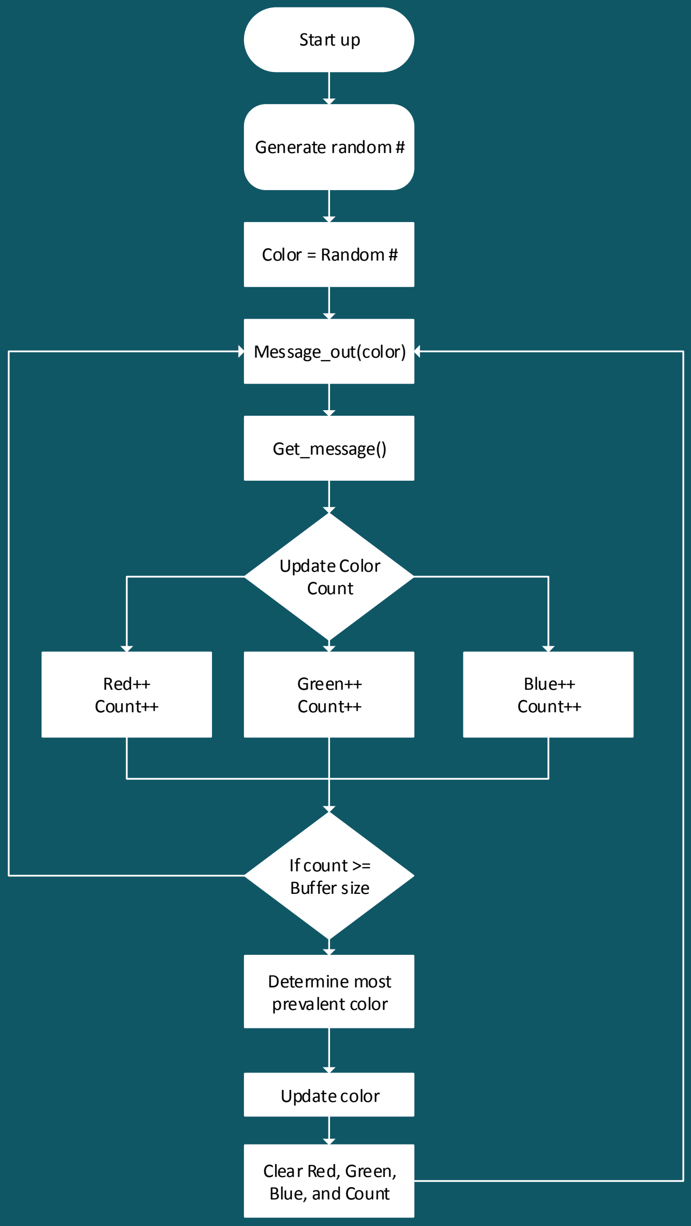
Motor Control



E-puck Tiny Bootloader



Color Consensus Flowchart



Localization Equations

- $C_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2}$
- $V_i = < \frac{x_0 - x_i}{C_i}, \frac{y_0 - y_i}{C_i} >$
- $n_i = (x_i, y_i) - D_i * V_i$
- $(x_0, y_0) = (x_0, y_0) - \frac{(x_0 - n_{ix}, y_0 - n_{iy})}{4}$