Proposal Title: L-CAS: Local-Frame Collision Avoidance System for Non-Line of Sight Autonomous Systems

In Response to Intel's America's Greatest Maker Season 2

Lead Proposer Organization Name:
Lofaro Labs Robotics - DASL Group - George Mason University (501(c)3)

Type of Business: 501(c)3

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Place(s) of Performance:
George Mason University
Laboratory for Autonomous Systems Research - Naval Research Labs

Period(s) of Performance: 3 Months

Robotics Fast Track (RFT)

Proposal Title:
L-CAS: Local-Frame Collision Avoidance System for Non-Line of Sight Autonomous Systems

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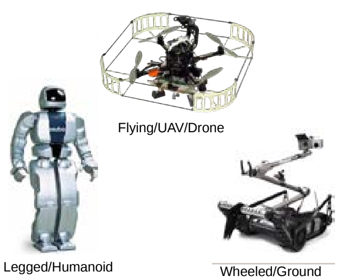
Lofaro Labs Robotics
DASL Group
George Mason University

L-CAS: Local-Frame Collision Avoidance System for Non-Line of Sight Autonomous Systems

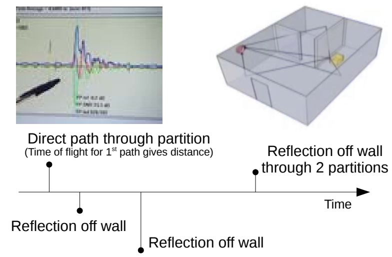
Portable System for Formation Keeping and Increased Situational Awareness for Heterogeneous Non-Line of Sight Autonomous Systems



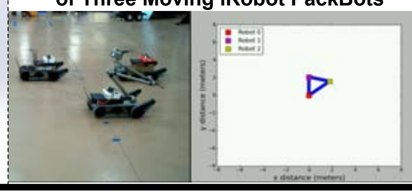
Mounting Points for Various Robot Types

- Ultra-Wideband (IEEE802.15.4-2011)
- Two way ranging
- 5 hz position update rate (with 5 active robots)
- 20 m (~65 ft) Radius Localization range
- 20cm precision (indoor)
- 5 m/s (~11 MPH) Max Relative Velocity
- 200 g weight (less then the Pelican UAV max payload)
- Platform Independent (Socket/Ethernet Interface)

Ultra Wideband allows us to Distinguish between all the different paths between each Robot



L-CAS (βeta): Local-frame Localization of Three Moving iRobot PackBots



Executive Summary

L-CAS is a localization system that allows for increased situational awareness in homogeneous and heterogeneous mixtures of autonomous systems and humans. Each autonomous agent (robot and/or human) can carry an L-CAS unit. The relative distance between each L-CAS unit is determined using a multi-path resistant radio frequency ranging system. These distances are then shared between all L-CAS units. The relative formation of the group is determined by the using the distance from each L-CAS and implementing two and/or three-dimensional trilateration. Trilateration results in the location of each L-CAS unit in the local frame. The multi-path resistant nature of the ranging system means that this system can be used in non-line-of-sight circumstances (e.g. separated by walls, trees, etc.) while retaining formation information. This information increases situational awareness of all autonomous units.

Rough Order of Magnitude and Schedule

Phase / Deliverable	Schedule	Cost
Milestone 1: L-CAS (R3) Completion	Month 1-2	$4,440
Milestone 2: 2D Formation Tests (V.R3)	Month 2-3	$2,360
Milestone 3: 3D Formation Tests (V.R3)	Month 2-3	$1,760
Milestone 4: ROS/Ach/Gazebo-Sim Model	Month 2 and 4	$1,480
Milestone 5: 2D Formation Keeping (Simulated)	Month 4-5	$1,960
Milestone 6: L-CAS (R4) Completion - Final	Month 5-6	$3,280
Milestone 7: 2D Formation Tests (V.R4)	Month 6	$1,560
Milestone 8: 3D Formation Tests (V.R4)	Month 6	$1,560
Milestone 9: 3D Formation Keeping (Simulated)	Month 4-6	$2,400
Milestone 10: 2D Formation Keeping (Real)	Month 7	$1,800
Milestone 11: 3D Formation Keeping (Real)	Month 7-8	$2,000
Milestone 12: Human in the Loop Formation Keeping	Month 3 and 8	$3,560
Milestone 13: Final Deliverables and Demonstration	Month 4 and 8	$2,800
Equipment and Materials	-	$68,535
F&A (Indirect – 54.3%), Fridge, and Miscellaneous	-	$36,192
Travel (Testing, Demos, and Conference)	-	$6,817
Total	8 months	$144,305

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Contents

1 Executive Summary

This document proposes the creation of a system that gives robot-robot, robot-human, and human-human teams increased situational awareness by giving the user (robot and/or human) the location and formation of the other robot and/or human team members relative to themselves in non-line-of-sight and GPS denied environments. This system is called Local-Frame Collision Avoidance System (L-CAS).

The PI has completed a functional *Beta* version of L-CAS. The following link shows local-frame localization of three robots (iRobot PackBots) while moving in formation:
http://lofarolabs.com/projects/lcas/

L-CAS is a localization system that allows for increased situational awareness in homogeneous and heterogeneous mixtures of autonomous systems and humans. Each autonomous agent (robot and/or human) can carry an L-CAS unit. The relative distance between each L-CAS unit is determined using a multi-path resistant radio frequency ranging system. These distances are then shared between all L-CAS units. The relative formation of the group is determined by the using the distance from each L-CAS and implementing two and/or three-dimensional trilateration [1, 2]. Trilateration results in the location of each L-CAS unit in the local frame. The multi-path resistant nature of the ranging system means that this system can be used in non-line-of-sight circumstances (e.g. separated by walls, trees, etc.) while retaining formation information. This information increases situational awareness of all autonomous units.

1.1 Objective

L-CAS relates to the field of localization systems. More specifically, it comprises of non-line of sight capable methods for one to six dimensional localization between 2 or more parties in a local frame of reference. Parties can be comprised of human and non-human agents or a combination thereof.

It is proposed to further the development of this system and give it three-dimensional (translational) local-frame formation tracking capabilities. The other three dimensions (rotational) will be added in future works if needed. The formation tracking will be tested on ground and air robots moving at speeds in excess of $5\frac{m}{s}$ ($11\ Mph$).

The final L-CAS will be a light weight device that can be easily carried by an autonomous system (ground, air, or human). The robot interface will be via standard and ubiquitous communications methods, and the human interface will be via a smart handheld or wearable device.

1.2 How it is done today and limitations

Humans and non-human agents (such as robots) need to know where they are in the world. The current most prevalent example of this is the use of GPS (Global Positioning System). GPS gives the user their 2-3 DOF (Degree of Freedom) location in the world frame (external frame). GPS uses static landmarks such as satellites, cellular towers, and wireless "hot-spots" to determine the users location using the time difference of arrival between and trilateration techniques. The resulting spatial accuracy is on the order of meters (typically

1-3 meters) and does not include rotational information. The rate of new spacial coordinates for traditional GPS units is 5 reading per-second (5 Hz) or less. GSP units in conjunction with IMUs (Inertial Measurement Units) can give you global rotation information as well as improve spatial accuracy and temporal feedback rate.

The LORAN (LOng RAnge Navigation) system also uses stationary towers to determine a users location. LORAN was used by the United States during World War II. It utilizes a "ping" style time difference of arrival to these towers and pre-defined charts to determine a location on the order of hundreds of meters. Though the update rate is higher then that of GPS it still relies on stationary objects for localization.

1.3 Audience and Impact

The target audience for the L-CAS is any homogeneous or heterogeneous mixture of humans and/or robots that need to know where other agents from their group is relative to themselves.

Formation tracking and localization is required for many forms of robotics. The most popular current methods of localization are motion capture, visual tracking, and GPS. All of the latter methods are used to keep robots in formation (e.g. drone formation flying). A limitation of motion capture is that it does not work when the robot is outside of the very structured pre-defined work space. GPS does not function well (if at all) indoors and by definition can not be used in GPS denied environments. Visual tracking methods will not work because our target situation is takes place in a non-line-of-sight environment (see Section 2.9.1.

When L-CAS is completed robotic, human-robot, and human-human teams will be able to track their team members location relative to themselves and keep formation. This is important for team situational awareness, collaborative actions, and much more.

1.4 Place of Performance

This project will be carried out in the PI's lab Lofaro Labs Robotics at George Mason University as a part of the DASL Group. The large scale tests will take place at Laboratory for Autonomous Systems Research - Naval Research Laboratory (LASR-NRL). The PI has worked at LASR-NRL as an ONR-SFRP fellow and retains good working relationship with the lab. The director of LASR-NRL Alan C. Schultz has given the PI permission to use the facility for this project and other research purposes.

1.5 Total Cost and Time to Completion

The L-CAS can be completed at a cost of $144,305 in a time frame of 8 months.

2 Technical Description

The PI proposes to make a system that allows for formation tracking of multiple autonomous agents in non-line-of-sight and GPS denied environments. The proposed method is a new implementation of a ranging method formally only used tracking in pre-defined areas. The specifications of the proposed system is defined in Section 2.1. To achieve this we need to do the following:

- Unit to Unit Ranging: Find the distance between each L-CAS unit
- Unit to Unit Communication: Share the distance of all L-CAS units with each-other
- Formation Calculation: Determine local-frame formation
- Test on stationary and moving robots

The proposed project can succeed because the PI has created a beta L-CAS as a proof of concept. See Section 2.5 for explanation of the L-CAS beta.

2.1 Specifications

Below are the desired specifications for L-CAS . Each item listed feasibility is discussed in the subsections of Section 2.1.

- 40 cm accuracy (e_d)
- > 5 Hz formation update rate (f_d)
- 15 m localization radius (r_d)
- > 5 $\frac{m}{s}$ relative velocity (v_d)
- < 200 g total weight (m_d)
- Platform independent

2.2 Unit to Unit Ranging

The ranging will be done via using Ultra-Wideband (IEEE802.15.4-2011) time of flight (ToF) ranging. Current versions of L-CAS uses the DW1000 transceiver from DecaWave[1] due to it's ability for two-way ranging and resistance to multi-path. Two-way ranging is facilitated by the built-in 6.8 $Mbps$ wireless network which allows sharing of distances. Resistance to multi-path is determined by reading the ToF of the first time the coded packet is received, see Figure 1.

The DWM1000 states that it has 10 cm ranging accuracy. During the testing of our L-CAS R1 (first generation) we determined the standard deviation from ground truth (from individual units) to be 2.33 cm in ideal conditions, see Figure 6. Please note that this is significantly less then our desired accuracy e_d.

2.3 Unit to Unit Communication

The L-CAS currently communicates over a wireless 2.4 Ghz (IEEE-802.11g) ad-hoc network. Via this network each L-CAS unit shares the relative distance that each unit is from each-other. Latency has not been tested yet but will be. The latency must be less then $\frac{1}{f_d}$ where f_d is our desired update frequency in Hz.

If the latency tests do not yield the desired results we have the following alternatives:

[1]DecaWave: http://www.decawave.com/

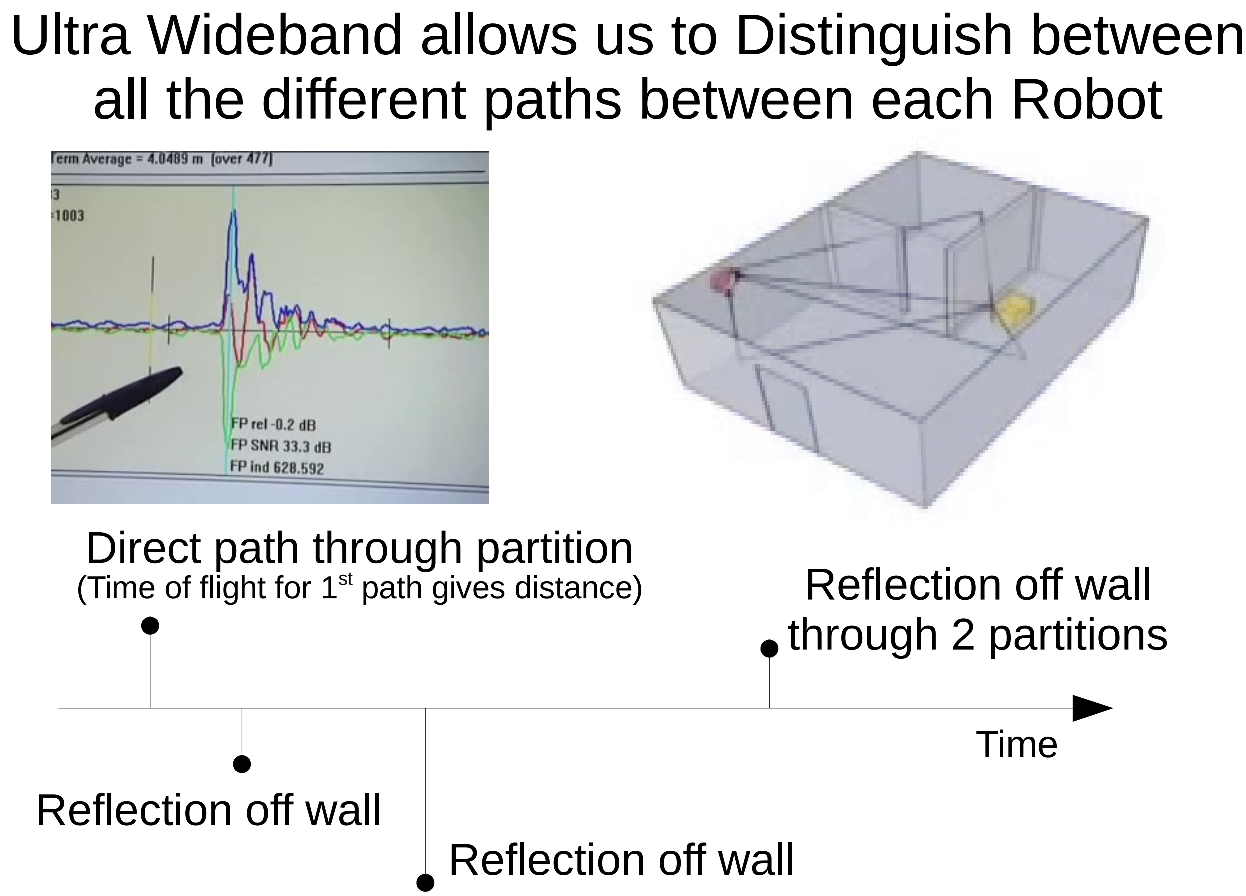

Figure 1: Ultra-Wideband (IEEE802.15.4-2011) multi-path resistant ranging method using the DecaWave DWM1000.

- Use 5 *Ghz* (IEEE-802.11ac) wireless communication. The 5 *Ghz* band is currently "less cluttered" then 2.4 *Ghz* which has many devices currently using the spectrum.
- Use the built-in 6.8 *Mbps* network in the DWM1000.

2.4 Formation Calculation

The formation is calculated via using trilateration. Trilateration is *"In geometry, trilateration is the process of determining absolute or relative locations of points by measurement of distances, using the geometry of circles, spheres or triangles."*[2] Figure 2 shows a 2 dimensional diagram of trilateration.

The L-CAS R1 implemented two dimensional (2D) trilateration using the distances found in Section 2.2 which were communicated via the methods in Section 2.3. L-CAS tests were performed at the Laboratory for Autonomous Systems Research (LASR) - NRL in Washington DC. Three iRobot PackBots were driven by human drivers in formation. Figure 4 shows frame captures from this test. It can be noted that the relative formation

[2]Trilateration: https://en.wikipedia.org/wiki/Trilateration (visited 2016-01-02)

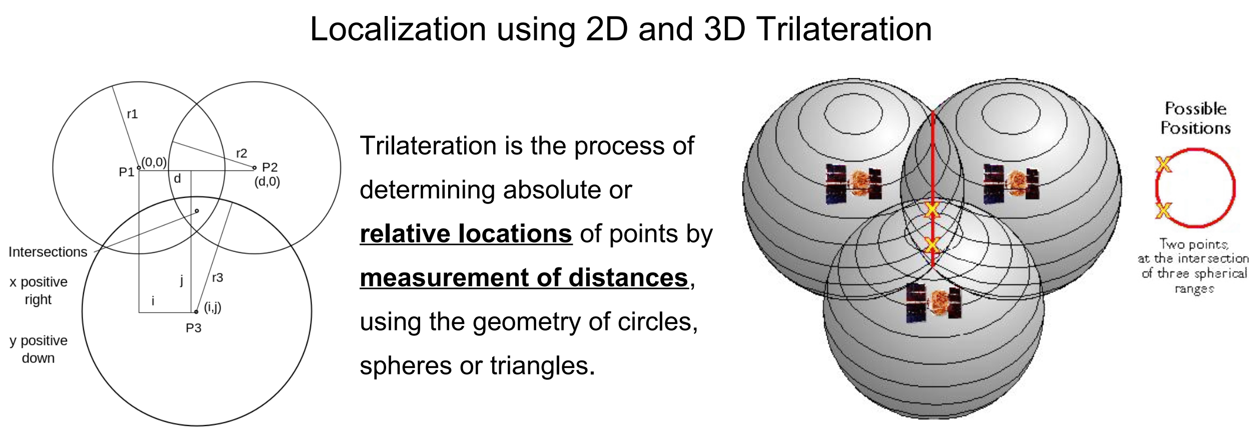

Figure 2: Trilateration is the process of determining absolute or relative locations of points by measurement of distances, using the geometry of circles, spheres or triangles.

is successfully tracked. In this test no ground truth was taken. Future tests will use LARS's motion capture system to get ground truth location data to compare against the formation determined by L-CAS . A video of the test found in Figure 4 can be found at *http://lofarolabs.com/projects/lcas/*

2.5 L-CAS αlpha and βeta Tests

The PI in conjunction with NRL have created an alpha and a beta version of L-CAS. The alpha version (L-CAS R1) can be seen in Figure 3. This version was able to have three devices connected at once. It could find the local-frame formation on three moving robots in real-time.

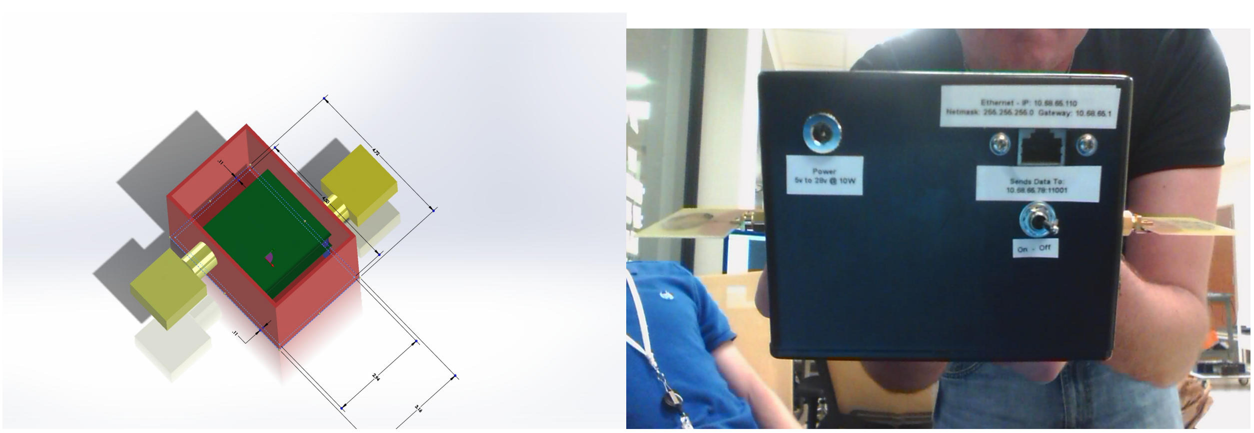

Figure 3: Left: L-CAS R1 mechanical/design model - Created by PI and NRL during 2015 ONR-SFRP. Right: L-CAS R1 completed unit - 4 units were made in total.

Figure 4 shows frame captures from the L-CAS R1 (alpha) test. The left of each frame is the actual video feed of the robots moving in formation. The right of each frame is the measured local-frame formation by the L-CAS R1. The test was performed at the Laboratory for

Autonomous Systems Research - NRL by the PI and his student Colin Ward (a Co-Proposer). A video of the test found in Figure 4 can be found at *http://lofarolabs.com/projects/lcas/*

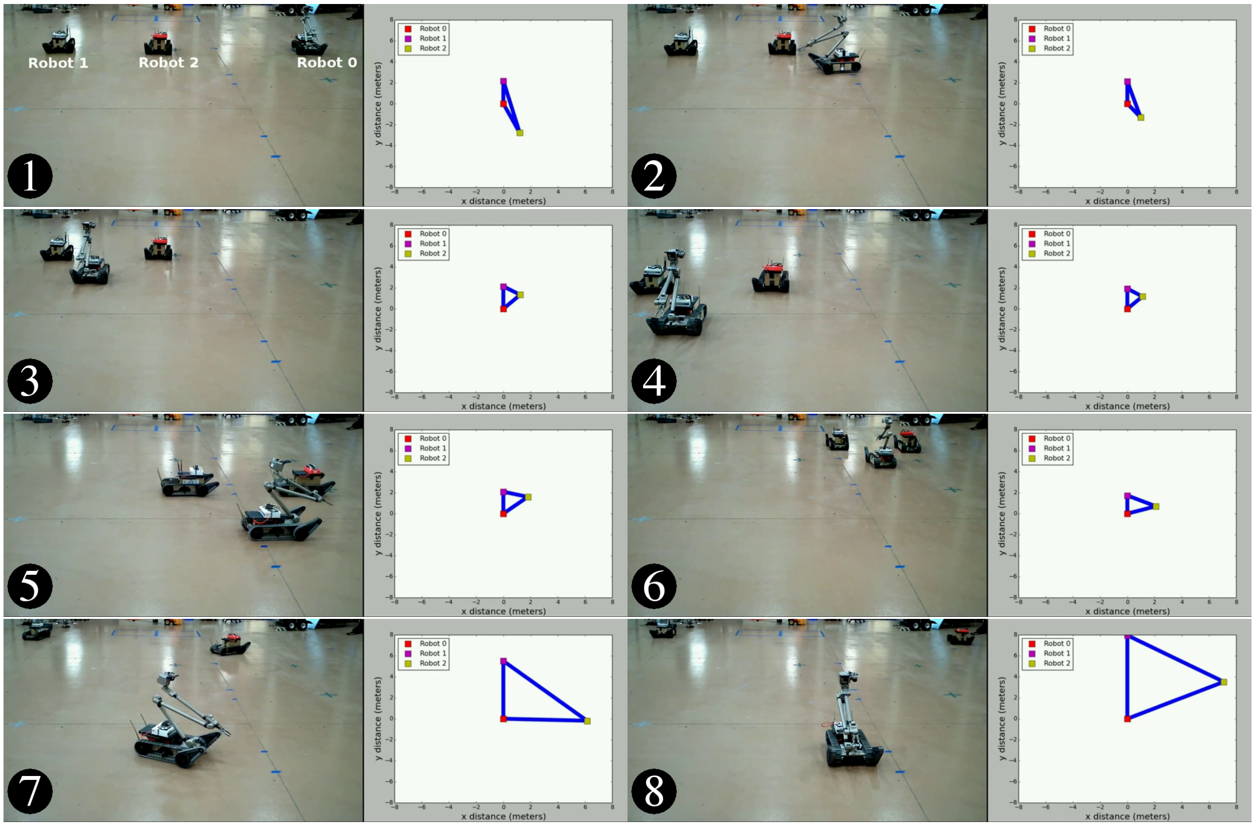

Figure 4: L-CAS test performed at the Laboratory for Autonomous Systems Research - NRL in Washington DC. Three iRobot PackBots were driven by human drivers in formation. Left shows external video feed of Robot 0, 1, and 2; Right shows the local-frame formation in reference to Robot 0. The frames are to be read from left to right, top to bottom (see frame number). Video for this test can be found at *http://lofarolabs.com/projects/lcas/*

The error between the ground truth and the L-CAS R1 measured distance was determined to have a standard deviation of 2.33 cm while in formation. 100 ranging samples were taken from each of the three robots. Please note that each L-CAS unit was calibrated using a constant bias and the ranging distance did not exceed 10 m. Figure 5 (Right) shows the calculated error for each of the three robots.

The L-CAS R1 (alpha) used two DWM1000 proto-boards, a custom case, external antennas, and other *Custom Off the Shelf* (COTS) items. Due to the COTS nature of the alpha system it weighted in at slight over 500 g and was not robust to external impacts due to the protruding antennas.

The beta version (L-CAS R2) drastically reduced the size and weight of the system by utilizing a custom circuit board and internal antennas. L-CAS R2 (beta) can be seen in Figure 5.

L-CAS R2 (beta) was used to test the 1D ranging accuracy at distance and determine a sufficient calibration order. Two L-CAS R2 units were placed at known distances, 1 m,

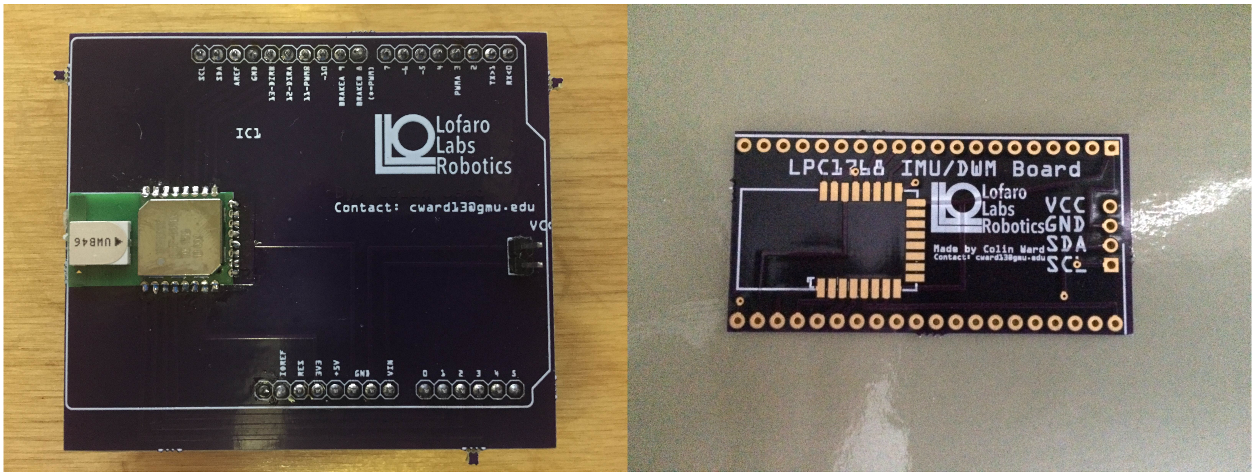

Figure 5: Left: L-CAS R2 (beta) - Created by PI at Lofaro Labs Robotics, improves upon the R1 version by decreasing size and reducing amount of radios while keeping ranging accuracy and speed. Right: L-CAS R2 (small) - small version of the L-CAS R2 unit. Designed to be more portable by flying vehicles.

5 m, 10 m, 15 m, ..., 45 m. Figure 6 shows the initial measured ranging data (red - pre-calibration).

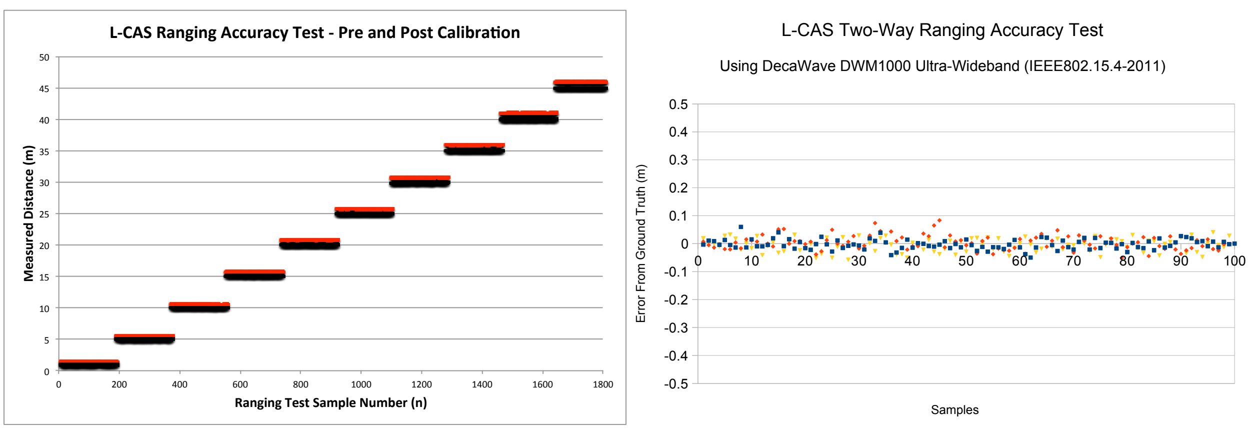

Figure 6: Left-Red: Initial measured ranging data (d_{mes}). Left-Black: Post-Calibration ranging data (d_{cal}) using a first-order calibration method. Right: Error between ground truth measurements and L-CAS ranging using the DWM1000. Three tests of 100 sample each were taken. The standard deviation was determined to be 2.33 cm in these ideal conditions.

The average error and standard deviation of the pre-calibrated data (d_{mes}) was then plotted (see Figure 7 - Left). A first-order line was fit to the data with the following coefficients: $m = 0.0119$ and $b = 0.4590$ with all base units in meters. This forms the first-order calibration equation:

$$d_{cal} = 0.119 d_{mes} + 0.4590 \tag{1}$$

The average error and standard deviation of the post-calibrated ranging data d_{cal} was then plotted (see Figure 7 - Right). The resulting error is well within our specifications defined in Section 2.1. The post calibrated data d_{cal} was then plotted on the same graph as the per-calibrated data d_{mes} (see Figure 6 - Black).

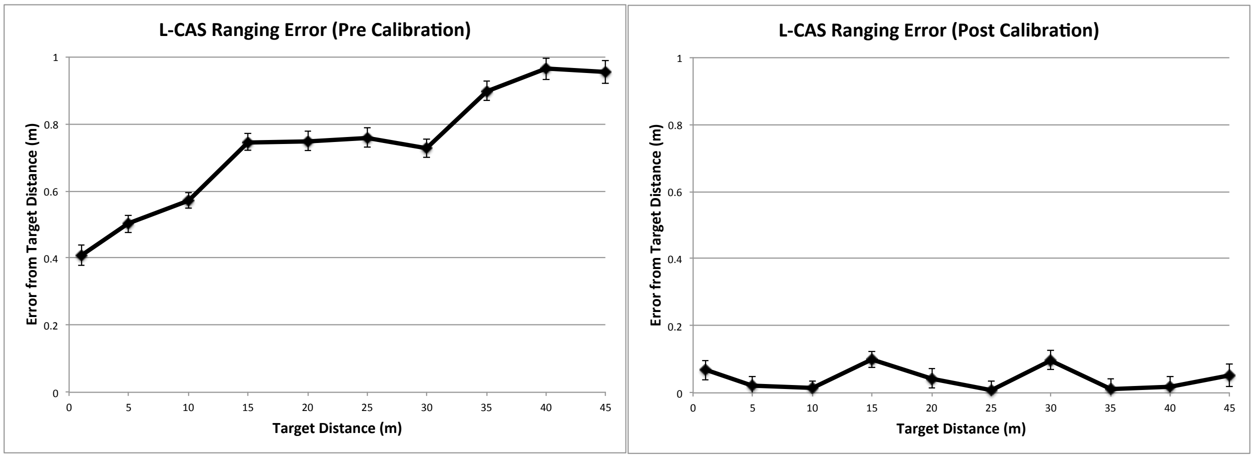

Figure 7: Left: Average error and standard deviation of the pre-calibrated (d_{mes}) ranging data. Right: Average error and standard deviation of the post-calibrated (d_{cal}) ranging data via a first-order calibration procedure. Both graphs are on the same scale.

The L-CAS R1 alpha and R2 beta tests show that it is possible that our system can achieve the ranging specifications as defined in Section 2.1.

2.6 Approach

The first step of the PI's proposed approach is the *Design I Stage* where the L-CAS R3 will be created based on the existing L-CAS beta system (R2). The R3 system will add support for the desired update rate, more robots, 3D formation tracking, and a smaller package size. While design is in progress the *Simulation I Stage* will begin with 2D and 3D open-loop formation tests. This will be developed in parallel with the *Design I Stage*. The controllers will be developed in such a way that there is no difference between controlling the simulated and real systems. This is one of the PI's expertise [3, 4, 5, 6, 7].

The R3 units will be calibrated via implementing open-loop formation tests during *Test I Stage*. Calibration will be done on the physical robots in the 2D and 3D frames. The ground robots were chosen because they can reach the desired speeds of over 5 $\frac{m}{s}$. The UAVs were chosen because of the need for a third dimension test platform that can carry the desired payload.

Once physical testing is complete it will be compared against the simulation results. The simulation will be updated to match that of the physical system.

Next is *Design Stage II* where L-CAS R4 will be developed with the goal of fixing any bugs or limitations found during the R3 testing. *Simulation II Stage* will in parallel. This stage will create 2D and 3D closed-loop formation keeping controllers the simulated system.

Once the R4 system is completed and calibrated, the open-loop and closed-loop 2D/3D formation tests will be carried out on the real robots. *Test II Stage* will calibrate the systems in the 2D and 3D frames. The open-loop formation test is the same test as before except being conducted on the R4 units.

The *Implementation Stage* will mark the finalizing of the L-CAS units. The closed-loop formation keeping test were previously on tested on the simulated system during *Simulation II Stage*. During *Implementation Stage* the closed-loop formation keeping will be implimented on the physical robots.

Once this finished the *Demonstration* will start. The Demonstration Stage is meant to show off the capabilities of the system. This is when we add a human in loop with the robots when tracking their formation. The human-in-loop formation keeping will be the final demonstration to DARPA.

Table 1 shows the milestones from Section **??** broken up into the *Approach Stages*.

Table 1: Milestones broken up into approach categories, e.g. Development, Simulation, Implementation, and Demonstration.

Approach Stage	Task/Milestone
Development I	Milestone 1: L-CAS (R3) Completion
Test I	Milestone 2: 2D Formation Tests (V.R3) Milestone 3: 3D Formation Tests (V.R3)
Simulation I	Milestone 4: ROS/Ach/Gazebo-Sim Model Milestone 5: 2D Formation Keeping (Simulated)
Development II	Milestone 6: L-CAS (R4) Completion - Final
Test II	Milestone 7: 2D Formation Tests (V.R4) Milestone 8: 3D Formation Tests (V.R4)
Simulation II	Milestone 9: 3D Formation Keeping (Simulated)
Implementation	Milestone 10: 2D Formation Keeping (Real) Milestone 11: 3D Formation Keeping (Real)
Demonstration	Milestone 12: Human in the Loop Formation Keeping Milestone 13: Final Deliverables and Demonstration

2.7 Technical Challenges

There are two major technical challenges **1)** Achieving the desired update rate and **2)** Determining the correct orientation of the formation. This section describes how each of the latter technical problems will be addressed and what the backup plans are.

2.7.1 Achieving the Desired Update Rate

The update rate of the ranging of L-CAS is limited by the bandwidth of the chosen ranging system. The DecaWave DWM1000 is the chosen ranging system and support a total of 392 ranging measurements per second per channel. Each DWM1000 can run on one of two channels at a time, 4 *Ghz* or 6 *Ghz*. The DecaWave DWM1000 ranging system was chosen due to it's multi-path resistance and ability to measure threw walls. Those are key features of our system, thus we do not want to change ranging methods.

In order to determine the formation each L-CAS unit needs to know how far it is away from the other units. The L-CAS R1 and R2 does all ranging twice, once from Robot A to

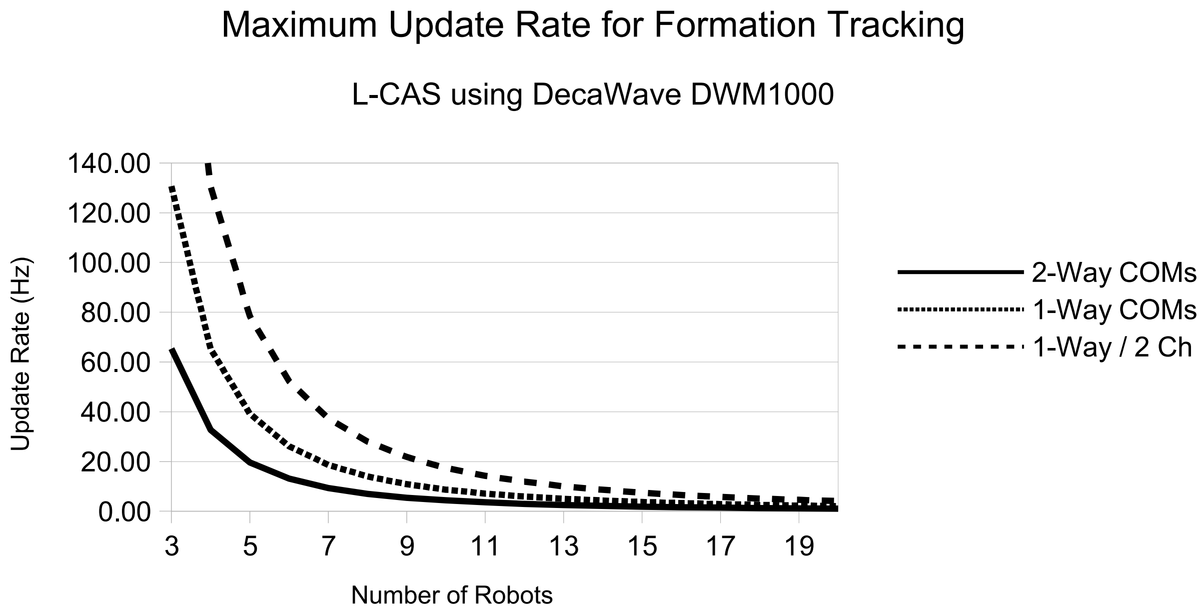

Figure 8: Maximum update rate for the L-CAS system when utilizing the DecaWave DWM1000 in 1-Way, 1-Way 2-Channel, and 2-Way ranging mode.

B and once from B to A. This is done because by default only one side knows the resulting distance per request, thus the other side needs to ask. This means that the number of ranges needed is equal to $n_r(n_r - 1)$ where n_r is the number of L-CAS units you are determining the formation of. The resulting update rate (f_2) for this *2-way* ranging method is:

$$f_2 = \frac{f_m}{n_r(n_r - 1)} \tag{2}$$

Where f_m is the maximum update rate of the DMW1000, $f_m = 392$. Figure 8 shows the maximum update rate f_2 with n_r L-CAS units when utilizing the *2-way* ranging method. The graph starts at 3 robots/L-CAS because that is the minimum you need to form a 2D formation.

To increase the update rate you need to reduce the number of times you range over the network. One method is to range once from Robot A to B (now Robot A knows the distance) then send Robot B the measurement from Robot A over a secondary network, such as an 802.11x Ad-Hoc. Now both Robot A and Robot B know their distance between each other and they only had to range once. This makes the number of ranges required equal to $n_r(n_r - 1)/2$ when utilizing this *1-way* ranging. The resulting update rate (f_1) for this *1-way* ranging method is:

$$f_1 = \frac{f_m}{n_r(n_r - 1)/2} \tag{3}$$

This will be more useful when the number of robots grows because we would need to transfer that data to the other robots any way. Figure 8 shows the maximum update rate f_1 with n_r L-CAS units when utilizing the *1-way* ranging method.

Using *2-way* ranging, to achieve our desired formation update rate f_d of 5 Hz we can not have any more then 9 robots in our formation. If we use *1-way* ranging and a secondary network we can have up to 13 L-CAS enabled robots in our formation. These numbers are in ideal circumstances.

If we need more robots in our formation then *1-way* ranging will allow for and still achieve f_d our backup plan is to use multiple ranging bands/channels. As stated previously the DWM1000 is configurable to run on the 4 Ghz band and on the 6 Ghz band. Each L-CAS can have two DWM1000 ranging systems, one running on each band/channel. Now each L-CAS can range in parallel to different units on different bands/channels. If we use *1-way* ranging over these 2 bands/channels we will achieve twice the ranging bandwidth then we previously had. This gives us the *1-way 2 channel* update rate (f_c) of:

$$f_c = 2\frac{f_m}{n_r(n_r - 1)/2} \tag{4}$$

Figure 8 shows the maximum update rate f_c with n_r L-CAS units when utilizing the *1-way 2 channel* ranging method. This method can support up to 18 L-CAS enabled robots achieving a formation update f_d greater than 5 Hz.

The PI plans on implementing the *1-way* ranging method to achieve f_1 due to it's simplicity over the *1-way 2 channel* requirement to pair L-CAS device frequencies. If greater ranging rates are required the PI will implement the *1-way 2 channel* method.

2.7.2 Determining the Correct Orientation of the Formation

When using trilateration methods as described in Section 2.4 the orientation of the formation can be mirrored over at minimum one axis. In addition the formation can be rotated about any axis because it is a local-frame formation received via ranging data from n_r robots at unknown locations (assuming 2D or 3D formation tracking).

The critical problem here is that there is no landmarks to supply formation orientation data (e.g. no known object). The key to solving this is to get a landmark. The goal of L-CAS is to work in non-line-of-sight and GPS denied environments thus we can not use visual cues or GPS. What we can use is gravity, the Earth's magnetic field, and the estimated motion of the other L-CAS units.

By using an inertial measurement unit (IMU) we can find a common up and down via finding the gravity vector on each L-CAS enabled robot. The gravity vector will be the same for each robot due to their relatively close proximity to each-other. The formation is no longer free to rotate about the horizontal axises (x and y).

The formation is still free to rotate about the vertical axis (z). This is where the Earth's magnetic field and the estimated motion of the L-CAS units come in. Each robot can find it's own orientation via the magnetic field. Even in areas where there is magnetic interference, each robot will probably be experiencing similar magnetic biases due to their relatively close proximity. A state estimator can then feedback the movement of the robot. This motion and orientation estimation can be distributed along with the ranges.

A backup plan would be that the user calibrates the system at startup and orients the formation to what it really is. The user would have to re-orient the formation in the z axis unless state information is fed back from the other L-CAS units.

2.8 Measure Progress and Success

The measures of success are primarily based on achieving the Section 2.1.

2.8.1 Accuracy

If the measured error (e_m) between (Euclidean distance) the target location of the robot and the actual location of the robot as measured from L-CAS is less than or equal to e_d then the system is individually successful for *Accuracy*.

$$e_m \leq e_d \tag{5}$$

Progress will be measured by what percent (%) the achieved e_m is away from e_d.

2.8.2 Update Rate

If L-CAS provides unique formations at a rate f_m which is greater than or equal to the desired update rate f_d then the system is individually successful for *Update Rate*.

$$f_m \geq f_d \tag{6}$$

Progress will be measured by what percent (%) the achieved f_m is away from f_d.

2.8.3 Localization Radius

If L-CAS can provide a formation when the widest width of the formation (d_m) is greater than or equal to twice the desired maximum localization radius r_d then the system is individually successful for *Localization Radius*.

$$d_m \geq 2r_d \tag{7}$$

Progress will be measured by what percent (%) the achieved d_m is away from $2r_d$.

2.8.4 Relative Velocity

If L-CAS can provide a formation when the relative velocity (v_m) of two or more L-CAS units is greater than or equal to the desired maximum velocity v_d then the system is individually successful for *Relative Velocity*

$$v_m \geq v_d \tag{8}$$

Progress will be measured by what percent (%) the achieved v_m is away from v_d.

2.8.5 Total Weight

If one L-CAS unit weights (m_m) less than or equal to the desired total weight m_d then the system is individually successful for *Total Weight*.

$$m_m \leq m_d \tag{9}$$

Progress will be measured by what percent (%) the achieved m_m is away from m_d.

2.8.6 Platform Independent

If L-CAS can run on Mac, Windows, and Linux platforms then the system is individually successful for *Platform Independent*.

Progress will be measured by how many platforms (unique operating systems) L-CAS runs on.

2.8.7 Wholly Successful

If L-CAS meets all of the requirements in this section simultaneously then the system will be *Wholly Successful*.

2.9 Who Benefits from this Technology

The target audience for the L-CAS is any homogeneous or heterogeneous mixture of humans and/or robots that need to know where other agents from their group is relative to themselves.

2.9.1 Hypothetical use of L-CAS

Two soldiers and a group of robots are clearing a floor of a building. They walk in, the first soldier has three robots on the left and two robots plus one human on the right. The humans and the robots are staying in formation. As the first soldier walks through the building some robots take Hallway A and other Hallway B, and the second soldier takes the parallel hallway. By briefly looking at their L-CAS enabled smartwatch the soldiers always knows where their team members (robotic and human) are relative to themselves even in non-line-of-sight conditions.

2.9.2 Other Use Cases

Example Usage 1: Formation Keeping
A fleet of autonomous systems such as Unmanned Aerial Vehicles (UAV) and Unmanned Ground Vehicles (UGV) can use the local frame location information to keep in a relative formation. This can be done by servoing off of the received position from the L-CAS .

Example Usage 2: Collision Avoidance
A fleet of UAVs and/or UGVs can use the information from L-CAS to avoid each other without the need for other sensors.

Example Usage 3: GPS Location Expansion in GPS Denied Environments
A fleet of UAVs and/or UGVs can move into a GPS denied Environments (such as indoors) and determine the global location of all units as long as one of the units in the formation maintains GPS coverage.

Example Usage 4: Formation Keeping with Humans

One or more human users can maintain awareness of the location of their team members (human or robot) via the formation readout being posted on a tablet, smartwatch, or other smart display like Google Glass. This will allow the human user to stay in formation with their team mates, as well as allow their team mates to stay in formation with them.

3 Capability/Technology Information

This solicitation is the first to which this capability/technology (L-CAS) has been proposed. The L-CAS was started during a Office of Naval Research (ONR) Summer Faculty Research Program (SFRP) at the Naval Research Laboratory (NRL) that the PI was awarded in the Summer of 2015. The PI's colleagues from the 2015 ONR-SFRP will continue to be apart of the L-CAS project (see Section **??**).

The PI has completed a functional *proof-of-concept* prototype of L-CAS. It is capable of two-dimensional (2D) formation acquisition with 3 robots. The following link shows local-frame localization of three robots (iRobot PackBots) while moving in formation:
http://lofarolabs.com/projects/lcas/ The proposed L-CAS is to support three-dimensional (3D) formation acquisition as well an order of magnitude larger number of L-CAS robots/users in the formation.

4 Interactions with the Robotics Research Community

The PI is the director of the Lofaro Labs Robotics team at a part of the DASL Group at George Mason University. Through the Lofaro Labs and DASL Group the PI has been an active and published member of the Robotics Research community since 2008. The PI has managed and developed multiple systems used in the robotics research community.

The PI is active in his professional, DYI, and STEM communities. Currently the PI expands his research outside of the GMU campus by working at the Naval Research Laboratory (NRL) over the summer via the ONR-SFRP (awarded in 2015, awaiting reply for 2016 application). The PI utilizes undergraduates for research via the Office of Scholarship, Creative Activities, and Research (OSCAR) program at GMU. Demonstrations and invited talks are a common occurrence for the PI and his lab (see Section 4.4 and 4.5.2. The PI also has applications out for competing in RoboCup Rescue and the Amazon Picking Challenge at RoboCup 2016.

In an effort to gain more machining expertise the PI has started a BattleBots and Robot-Wars team (120 *lb* and 220 *lb* weight class). This requires the students to machine and focus on durability. Starting February 2016 the PI will utilize the DARPA TechShop located in Arlington (Crystal City), VA for machining classes for his research students.

4.1 DARPA Robotics Challenge (DRC) Track A team DRC-Hubo - Research Lead

The PI was the research lead for the DARPA Robotics Challenge (DRC) Track A *Team DRC-Hubo*. In doing this the PI coordinated and integrated the research efforts from 10 universities, 14 professors and more then 50 students. After the DRC 2013 Trials the PI moved to a faculty position at George Mason University but continued to work with *Team DRC-Hubo*. *Team DRC-Hubo* earned 8^{th} place at the DRC 2015 Finals. The robot *DRC-Hubo*, which was a result of the design research from *Team DRC-Hubo*, earned 1^{st} place via *Team KAIST*. The PI's efforts also resulted in multiple peer-reviewed publications (see Section 4.4).

4.2 Leadership

This section shows select leadership activities performed by the PI and the Lofaro Labs. For a complete list see the PI's Curriculum Vitae (CV).

4.2.1 International Program Committee member (URAI 2015-2016)

International Program Committee member International Conference on Ubiquitous Robots and Ambient Intelligence (URAI) in 2015 and 2016. The aim is to bring together academics, researchers, engineers, and students worldwide to discuss the state-of-the-art technology and to present recent works related to the various aspects of all kinds of robots.

4.2.2 RoboCup Team Robo-Patriots Co-Advisor

The RoboPatriots compete in the "kid-size" humanoid robot soccer league at RoboCup, an annual international autonomous robotic soccer competition. The 2015 RoboPatriots are a joint effort of the GMU Autonomous Robotics Laboratory and the GMU Lofaro Labs, and are sponsored by the National Science Foundation and by Tom Bihn.

4.3 Products and Software

This section shows select products and software made by the PI and the Lofaro Labs. For a complete list see the PI's CV and the Lofaro Labs website at: *http://LofaroLabs.com*

4.3.1 Hubo-Ach: Control System for the Hubo and DRC-Hubo Robots

Started in May 2012, Hubo-Ach is a low level controller for the Hubo 2, Hubo 2+, and DRC-Hubo platforms designed by Daniel M. Lofaro (PI) and Neil Dantam[3]. It works seamlessly on adult-size, kid-size, and simulated versions of the Hubo platforms allowing for Rapid Prototyping (RP), Test and Evaluation (T&E), and Verification and Validation (V&V). Hubo-Ach is OpenSource and is currently being actively used by:

- The Hubo's located at MIT, Georgia Tech, Perdue, Drexel, and UNLV
- *Team DRC-Hubo*

- George Mason University's undergraduate and graduate robotics classes

Hubo-Ach also works on the smaller Hubo/Hubo-like platforms such as the Mini-Hubo, DarwinOP, OpenHubo, and OpenDRC-Hubo.

4.3.2 OpenHubo and OpenDRC-Hubo Simulated Humanoids

Started in February 2011, OpenHubo and OpenDRC-Hubo is a dynamic simulation of the Hubo2/2+ and DRC-Hubo platforms respectively. OpenHubo and OpenDRC-Hubo are OpenSource and are currently being actively used by:

- The Hubo's located at MIT, Georgia Tech, Perdue, Drexel, and UNLV
- *Team DRC-Hubo*
- George Mason University's undergraduate and graduate robotics classes

OpenDRC-Hubo the result of the RP phase when developing the DRC-Hubo.

4.3.3 Apparatus for Remote Control of Humanoid Robots (ARCHR)

The ARCHR team from the Lofaro Labs made controllers that were mapped from the controller to the robot. We made a 1 to 1 scale which was Minibot, 44% scaled version of baxter, and a scaled version for Hubo DRC. The Hubo DRC was in a simulation and the controller was real telling the computer where to move the robot. The system was published and presented at IEEE Humanoids 2015 [8].

4.3.4 Magnetic Resonator Guitar (MR.G)

The Magnetic Resonator Guitar (MR.G) was created in 2014/15 by Lofaro Labs and was inspired by Drexel University's Magnetic Resonator Piano. Much like the Magnetic Resonator Piano, MR.G is a hybrid acoustic-electric instrument. While the sound is processed electronically, the music the guitar produces is entirely acoustic. There are no speakers, with the only amplification being in connection to the electromagnetic actuation. For a full description and demo audio/video of Mr. G please goto: *http://lofarolabs.com/projects/mrg/*

4.4 Publications and Presentations

This section shows the peer reviewed publications and presentations done by the Pi and Lofaro Labs for the past 5 years. For a complete list see the PI's CV. All works listed below were a publication and a presentation unless noted with an $*$, those are publication only.
List of publications/presentations:

- 2016:
  - Low Latency Bounty Hunting and Geographically Adjacent Server Configuration for Real-Time Cloud Control [9]
- 2015:

  - ARCHR - Apparatus for Remote Control of Humanoid Robots [8]
  - Feasibility of Cloud Enabled Humanoid Robots: Development of Low Latency Geographically Adjacent Real-Time Cloud Control [10]
  - *The Ach Library: A New Framework for Real-Time Communication [3]

- 2014:
  - A lightweight, cross-platform, multiuser robot visualization using the cloud [11]
  - From autonomy to cooperative traded control of humanoid manipulation tasks with unreliable communication: System design and lessons learned [6]
  - DARPA Robotics Challenge: Towards a user-guided manipulation framework for high-DOF robots [12]

- 2013:
  - A n-dimensional convex hull approach for fault detection and mitigation for high degree of freedom robots humanoid robots [13]
  - Unied Algorithmic Framework for High Degree of Freedom Complex Systems and Humanoid Robots [4]
  - Multi-process control software for HUBO2 Plus robot [5]
  - Toward a user-guided manipulation framework for high-DOF robots with limited communication [7]

- 2012:
  - Humanoid pitching at a Major League Baseball game: Challenges, approach, implementation and lessons learned [14]
  - Humanoid throwing: Design of collision-free trajectories with sparse reachable maps [15]
  - Humanoid throws inaugural pitch at Major League Baseball game: Challenges, approach, implementation and lessons learned [16]

- 2011:
  - Robot audition and beat identification in noisy environments [17]
  - Enabling humanoid musical interaction and performance [18]
  - *Towards a musically-aware humanoid for interactive music performance [19]

- 2010:
  - Developing humanoids for musical interaction [20]
  - Interactive Games With Humanoids: Playing With Jaemi Hubo [21]
  - Interactive musical participation with humanoid robots through the use of novel musical tempo and beat tracking techniques in the absence of auditory cues [22]

4.5 Invited Talks and Demonstrations

This section lists the invited talks and demos the PI and Lofaro Labs has done over the past 5 years. For a complete list see the PI's CV.

4.5.1 Invited Talks

- 2016:
  - Smithsonians National Air and Space Museum - Washington, DC. Speaker for kickoff to National Robotics Week 2016. Talk Title: Robots Across the Globe. (***Scheduled for April 1, 2016***)
  - Navy Center for Applied Research in Artificial Intelligence (NCARAI) symposium series at the Naval Research Laboratory, Washington, D.C. Talk Title: Working with Humanoids (***Scheduled for February 10, 2016***)
- 2015:
  - Smithsonians National Air and Space Museum - Washington, DC. Speaker for kickoff to National Robotics Week 2015. Talk Title: Design, Implementation, and Control of Disaster Relief Humanoid Robots.
  - Distinguished Lecture Series - Fairfax, VA. Talk Title: Team DRC-Hubo: The Road to the DARPA Robotics Challenge - Lessons Learned
  - IEEE-SPAC Student Professional Awareness Conference - Fairfax, VA. Talk Title: I Can Robot and You Can Too
- 2014:
  - Disney Research - Pittsburgh, PA. Talk Title: DARPA Robotics Challenge, Next Steps Forward
  - University of Zagreb -Zagreb, Croatia. Talk Title: Team DRC-Hubo: International Collaboration using a Three Phase Design Cycle
  - Bryn Mawr College - Bryn Mawr, PA. Talk Title: Building a robot club from the ground up (Part 2)
  - Society of Woman in Engineering (SWE) Invited Talk - Fairfax, VA. Talk Title: I can robot, and you can too - a cheat sheet for getting your Ph.D
  - Los Alamos National Laboratories - Los Alamos, NV. Talk Title: Team DRC-Hubo: International Collaboration using a Three Phase Design Cycle
  - Chung-Ang University - Seoul, S. Korea. Talk Title: Team DRC-Hubo: A US-Korea Collaboration
  - GMU Korea - Incheon, S. Korea. Talk Title: Team DRC-Hubo: A US-Korea Collaboration
  - Bryn Mawr College - Bryn Mawr, PA. Talk Title: Building a robot club from the ground up (Part 1)

- 2013:
  - Cornell University - Ithaca, NY. Talk Title: Team DRC-Hubo: A road-map to the DARPA Robot Challenge
- 2012:
  - University of Pennsylvania - Philadelphia, PA. Talk Title: DARPA Robot Challenge: The DRC-Hubo Team - Where we are and what we are doing
  - ASME - Drexel University - Philadelphia, PA. Talk Title: Humanoid Pitching at a Major League Baseball Game: Challenges, Approach, Im- plementation and Lessons Learned
  - Friends of the Free Library - Philadelphia, PA. Talk Title: Humanoid Robots, they are fun!
- 2011:
  - Philcon 2011 - New Jersey, NJ. Talk Title: Humanoid robots, a step in the right direction? About Philcon: Started in 1936, Philcon features cutting-edge programming about literature, art, television, film, anime, comics, science, gaming, costuming and cosplay, music, and other topics of interest to fans of sci-fi, fantasy, and horror.
  - State Senator Invitation - 5^{th} Annual Carole Smith Technology Symposium - Philadelphia, PA. Talk Title: Humanoid Robots, Past, Present, Future. 5th Annual Carole I Smith Technology Symposium. Hosted by State Senator LeAnna M. Washington, and Temple University
  - Daegu Institute of Science and Technology - Daegu, South Korea. Talk Title: Interactive Games With Humanoids.
  - Korean Advanced Institute of Science and Technology (KAIST) Daejeon, South Korea. Talk Title: Interactive musical participation with humanoid robots through the use of novel musical tempo and beat tracking techniques in the absence of auditory cues.
  - Hanyang University - Seoul, South Korea. Talk Title: Visual Beat Tracking
- 2010:
  - MY Robotics Club, Bryn Mawr College - Bryn Mawr, PA. Talk Title: Humanoid Robots, Past, Present, Future

4.5.2 Demonstrations

This section lists the live demonstrations that the PI and Lofaro Labs has performed over the past 5 years. For a complete list see the PI's CV.

- 2016:

- Smithsonians National Air and Space Museum - Washington, DC. Demonstration: Show the inner-workings of 3D printed humanoid robots to the do it yourself (DYI) community. Demonstration also includes a hands on experience with an adult size humanoid robot.
- HayMaker Faire - Haymarket, VA. Demonstration: Show the inner-workings of 3D printed humanoid robots, battle bots, and other exciting robots to the do it yourself (DYI) community.
- K-12 STEM Symposium. Demonstration: Ventures in the STEM fields including 3D printing, Robotics, and more.

- 2015:
  - Smithsonians National Air and Space Museum - Washington, DC. Demonstration: Showed the inner-workings of 3D printed humanoid robots to the do it yourself (DYI) community. Over 100k visitors that day.
  - Maker Faire - Washington, DC. Demonstration: Showed the inner-workings of 3D printed humanoid robots to the do it yourself (DYI) community.
  - Mini Maker Faire - Fairfax, VA. Demonstration: Showed the inner-workings of 3D printed humanoid robots to the do it yourself (DYI) community.
  - University of Nevada Las Vegas - Las Vegas, NV. Invited Professor: Seven day Jaemi Hubo Training session
  - Virginia legislature's House Appropriations and Finance Committee, Fairfax, VA. Demonstration: 3D printed humanoids, battle bot prototype, UAVs, and RoboCup team.
  - RoboCup 2015 Child-Size League in Hefei, China. Competed in RoboCup 2015 Child-Size League in Hefei, China: Reached the quarter finals.
  - K-12 STEM Symposium. with Virginia Senator Tim Kaine and Virginia Secretary of Education Anne Holton: GMU and the Lofaro Labs demonstrated their ventures in the STEM fields including 3D printing, Robotics, and more.
- 2013:
  - DARPA Robotics Challenge Trials, Homestead Maimi Speedway, FL. Team-DRC Hubo successfully competed in the challenge, attempting every task.
- 2012:
  - Columbia University - New York, NY. Demonstration: Hands on demonstration of the Hubo2+ humanoid robot. Following the demon- stration there was a in depth Q&A session with the graduate and undergraduate students in the college of engineering.
  - Maker Faire - New York, NY. Demonstration: Showed the inner-workings of Hubo the humanoid robot to the do it yourself (DYI) community.

  - MLB Baseball Game - Philadelphia Phillies and Philly Science Festival - Philadelphia, PA. Demonstration: Developed a system to make Hubo become the first full-size humanoid robot to successfully throw the inaugural pitch at a Major League Baseball game, Philadelphia Phillies vs. Chicago Cubs. 45,196 spectators according to the USA Today.
  - Friends of the Free Library - Philadelphia, PA. Demonstration: Included live hands-on demonstration of a miniature humanoid. Purpose what to get the inner city students exposed to advanced robotics.

- 2011:
  - Sugartown Elementary School - Sugartown, PA. Demonstration: Hands on demonstration and interactive sessions of ground vehicles, pick and place robots and miniature humanoids for elementary school students.

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