Multi-Tiered Safety for Warehouse Autonomous Robots

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Abstract

The Warehouse Autonomous Robots team (WAR) is partnered with Iowa Army Ammunition Plant (IAAAP) to develop a solution for the problem of integrating torque safety, vision safety, and passive safety while still performing the main function of autonomously picking up and moving cutoff 155mm rounds from one stationary location to another to another. We developed a novel solution consisting of a 6DOF arm capable of accurately detecting and autonomously picking up randomly dispersed rounds, all the while being able to cease operations after touching an obstacle and not dropping the round. Our final product is a 6DOF arm able to utilize depth and computer vision algorithms to detect round locations and iteratively determine a trajectory to said rounds. Additionally, the final product incorporates touch safety capabilities along with utilizing the unique geometry of a novel gripper design to passively hold the round. Our completely air-gapped system implements other cybersecurity principles to ensure only authorized access to our graphic user interface (GUI), through which parameters can be set and the arm can be controlled.

Index Terms

Automation, Robotics, Kinematics, Computer Vision, Safety, Computer Aided Design (CAD), Cybersecurity

I. Introduction

The Warehouse Autonomous Robots team (WAR) is partnered with Iowa Army Ammunition Plant (IAAAP) to develop a solution for the problem of integrating torque safety, vision safety, and passive safety while still performing the main function of autonomously picking up and moving cutoff 155mm rounds from one stationary location to another to another.

With an increased presence and reliance of robots in industry, there are increased risks to humans working in close proximity. The degree of safety that modern robots require ultimately depends on the degree to which they are expected to function alongside human workers. Although humans could feasibly be separated from the workspace of autonomous robots, most manufacturing environments would benefit from leveraging the ingenuity and creativity of humans while maintaining the speed and precision of robots; these environment require stringent safety standards to mitigate the risk of injuries and damages. There has been substantial work on establishing stringent safety standards in autonomous robots, but no current method has been successful in completely bridging the gap in human-robot interaction (especially robots that are capable of large scale manufacturing); even so-called “autonomous” robots that line the warehouses of industry giants such as Amazon, must still be caged off from human workers because they cannot dynamically respond to foreign inputs into their environment [1]. We aim to address this problem by implementing multi-tiered safety features for industrial application robots, specifically by simultaneously implementing (1) active safety (2) dynamic and autonomous path planning and (3) passive safety.

Within active safety, our robot must be able to respond to tactile stimuli like hitting an object and detect rounds real-time while filtering out false positives. Dynamic refers to the robot’s ability to move and adapt to its workspace, while autonomous refers to the robot’s ability to operate without human assistance. Thus, our robot must calculate and navigate its own unique trajectory to randomly dispersed rounds within all three axes of a Cartesian coordinate frame and be able to respond to changing round locations. Passive safety refers to the robot safely operating even in the absence of power, and therefore the robot must be able to actively interface with the round using its own geometry and the geometry of the round.

To ensure that the final product can be realistically implemented in a warehouse environment, the additional subsystems of cybersecurity and a user-friendly GUI were also developed as means to streamline testing and to secure the integrity of the system as a whole.

II. Background Research and Related Work

Earlier WAR research projects focused on implementing active safety by developing and incorporating a “smart” battery management system (BMS) on an autonomous robot capable of monitoring and regulating DC voltage from LiPo batteries to power the main motors of the vehicle and all onboard functions. Previous research has also been done on detecting foreign objects using built-in torque sensing on robotic actuators and computer vision in conjunction with sensors, but the difficulty faced by more complex applications, such as a robotic arm picking up randomly dispersed circular artillery rounds, is that the robot needs to detect foreign interference while accurately detecting desired objects and filtering out false positives. Previous research developed a gripper that, while capable of suspending a round during motion, was unable to do so without active power [2]. This research project not only expands upon the scope of previous research but addresses the shortfalls of previous iterations. Some alternative ideas, like an automated gantry system, were also considered but ultimately determined to be too cost ineffective, limited in terms of modularity, and incongruent with the automation integration plans of IAAAP.

The current industry standards for dynamic robots is that they must be caged, or otherwise physically separated from human workers IAW ISO/TS 15066. The exception is the increasingly prevalent use of collaborative robots (cobots), which is still limited to physical separation in the cases of dangerous items being transported (and potential droppage), fast movement speeds, etc [3]. This means that our project, to improve upon current industry standards, must address both holding dangerous objects securely (through passive safety), and fast movement speeds (through touch safety).

Implementing multi-tiered safety, and subsequently ensuring that management prioritizes safety measures, would ensure the well-being of workers and reduce the risk of accidents, especially in a warehouse environment with many moving parts and heavy machinery. There may also be economic factors to consider, such as the immeasurable human capital that safe automation can free up to perform more complex or rewarding tasks such as overseeing said automation.

III. Design Specifications

Our research has focused on addressing safety considerations for autonomous robots both in the case when power is supplied and when power is cut off. The basic components of our design are HEBI X-Series Actuators which composes the joints of the 6DOF arm, with each actuator able to receive and provide position, velocity, acceleration, and torque feedback Fig. 1.

Fig. 1. Robotic Arm made up of HEBI X-Series Actuators

When the robot is actively running, there are obvious risks to it and its surroundings, but the less obvious risks arise when the robot is not actively running. One example would be a robotic arm holding a sensitive object on an assembly line; such a robot which must be able to hold itself and the object up even in the case of a power shortage. Even after safety features are in place, if foreign stimuli cause a situation deemed unsafe per the programmed risk tolerance, the robot will still need to operate and adapt to the changing workspace. A robot that simply ceases operations after detecting a safety risk comes at the cost of productivity because a halted robot will lose countless hours of work waiting for a human operator to clear the obstacle and resume operations. Therefore, it is just as important to develop a path planning algorithm that can dynamically react to changes. We implemented multiple tiers of safety, where vision safety and torque safety are “active” safety features, and our novel gripper design is a “passive” safety feature Fig. 2. See Appendix A for a more detailed discussion of the design specifications.

A. Active Safety Features

Active safety refers to safety features that require power to operate and therefore rely on the robot to be actively running. WAR has developed active torque safety for a 6DOF arm on an ammunition manufacturing assembly line that can interrupt an operation if the robot bumps into an obstacle. The current state of active vision safety is limited to the detection of rounds,

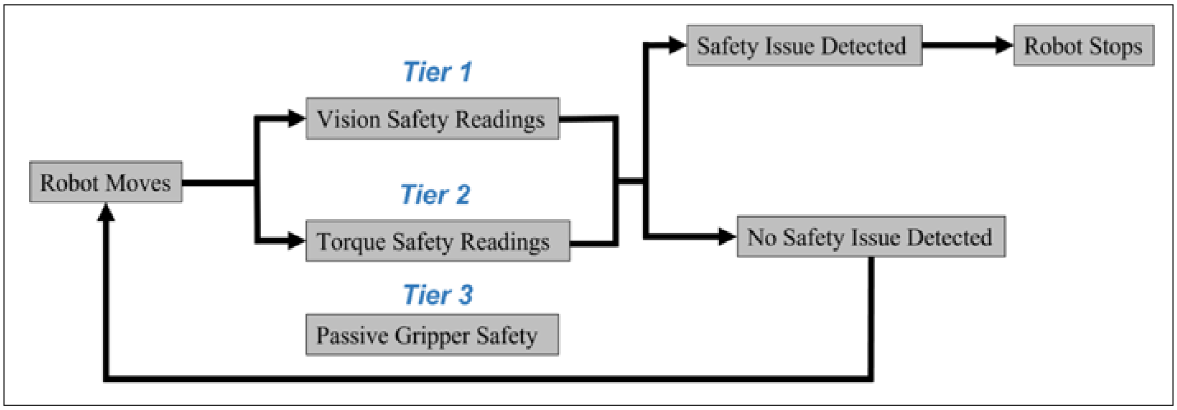

Fig. 2. Flowchart of multi-tiered safety

filtering out of false positives, and coordinate transformations to ensure that the coordinate frames of the camera and arm line up.

$$\bar{\tau} = \bar{r} \times \bar{F} = |\bar{r}||\bar{F}| \sin \alpha \bar{u}_{\tau} \tag{1}$$

$$\bar{F} = |\bar{F}|\bar{u_F} = \sum_{i=1}^{n} m_i g \tag{2}$$

$$\sin \alpha = \frac{\sqrt{r_x^2 + r_y^2}}{\sqrt{r_x^2 + r_y^2 + r_z^2}} \tag{3}$$

$$\bar{u}_{\tau} = \frac{-r_y \bar{u}_x + r_x \bar{u}_y}{\sqrt{r_x^2 + r_y^2}} \tag{4}$$

Torque safety compares the actual torque, gathered from live feedback from the HEBI actuators, to the dynamically calculated static torques. The static torque is calculated by converting the body fixed reference frame of each HEBI actuator to the base Cartesian frame, and then determining the position of the center of mass of each link in the base frame, per Equation 2. Then, the position of the center of mass of the arm relative to each actuator is calculated. The weight of the arm relative to each actuator is known and adjusted if the arm is carrying a round. The resultant torque is computed with the cross product of the distance to the center of mass of the arm and the weight force with respect to to each actuator, per Equation 1. If the actual torque feedback is significantly higher than the calculated torque, then the arm must have had a collision with an object, and subsequently pauses operations.

Static torque calculations will change depending on whether the arm has a round or not. To mitigate false positives, the torque calculations utilize a rolling average of feedback torque, which acts as a low-pass filter to remove noisy spikes in the measured torque, as depicted in Figure 3.

To address the difficulty of false positives with round detection, with the help of depth cameras, we developed a computer vision algorithm that simplifies the edges/contours of an image and then utilizing the Hough Transform with input parameters of minimum radius, maximum radius, accumulator, high/low gradients for edge detection, and resolution to return the center of all detected circles [4]. To reduce false positives, the robot uses a machine learning technique known as ensemble learning, which uses successive frames and detection criteria to "vote" for which pixels constitute a part of the desired object and then analyzing the "votes" to determine the pixel locations of said object. Then a circle is drawn around where the camera percieves is the center of the round as depicted by Fig. 4 [5]. By incorporating another dimension, depth, the computer vision algorithm can filter out rounds with even higher prevision. The benchmark for successful active safety implementation will be a comparison with the latest autonomous manufacturing robots, most of which are designed to be segregated from humans and thus do not possess close to the same robustness of safety implementation as what WAR proposes.

B. Passive Safety Features

Passive safety refers to the mechanisms in place that mitigate risk without the need of a power source. This often means that passive safety will rely on mechanical solutions such as exploiting intrinsic properties of the system, and incorporating counterweights, springs, or gears.

To address the issue of a robotic arm not dropping a round in the case of power loss, we developed a novel threaded gripper design that can passively hold an internally threaded object (such as a 155mm mortar round) by transferring the gravitational

		Module				
		Base	Shoulder 1	Shoulder 2	Elbow	Wrist
Move above round	Average Torque	1.23	0.997	0.515	0.504	0.317
	Max Torque	4.275	2.735	3.643	3.049	0.835
Engage Gripper	Average Torque	3.223	2.936	2.512	2.228	1.875
	Max Torque	7.086	7.018	5.492	4.917	4.174
Move down to round	Average Torque	2.984	2.687	2.386	2.091	1.789
	Max Torque	7.564	6.806	6.031	5.301	4.534
Disengage Gripper	Average Torque	1.356	1.22	1.084	0.952	0.819
	Max Torque	3.216	2.889	2.569	2.259	1.946
Move to home	Average Torque	2.764	2.49	2.212	1.936	1.655
	Max Torque	7.189	6.478	5.74	5.061	4.321
Move above destination	Average Torque	2.897	2.597	2.302	1.998	1.704
	Max Torque	7.185	6.458	5.744	5.007	4.255
Move down to destination	Average Torque	2.332	2.085	1.832	1.599	1.351
	Max Torque	6.592	5.93	5.263	4.613	3.929
Engage Gripper	Average Torque	1.613	1.452	1.292	1.127	0.965
	Max Torque	3.706	3.342	2.973	2.595	2.211
Move to home	Average Torque	1.153	1.036	0.92	0.808	0.697
	Max Torque	2.939	2.658	2.379	2.081	1.785

Fig. 3. Average and Maximum Torque by arm action

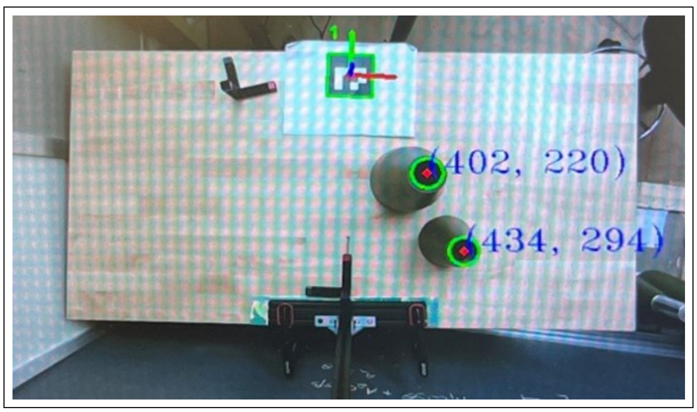

Fig. 4. Image of detected partial 155mm mortar rounds

force exerted on the object into a shear force dispersed evenly between the threads of the gripper and the threads on the object as shown in Fig. 5.

C. Dynamic Path Planning Algorithm

The arm's movement algorithm is determined by first using forward kinematics to determine the cartesian coordinate of the end effector given the angle feedback of each actuator. Then, the algorithm maps a straight line between its current coordinate and the desired coordinate. Next, a numerical method similar to the Newton Raphson Method is used to iteratively solve for the joint angles (within a specified tolerance) necessary to produce a certain desired position and orientation of the end effector.

IV. Analysis

The 6-DOF arm is capable of transporting 155 rounds from one location to another. Since the HEBI modules used as actuators for the arm produce a peak torque of 30 N-m, the current design is a proof of concept, and follow-on operations will be conducted for proof of scale. The arm is intended to demonstrate integration of safety systems with modern manufacturing capabilities to safely automate production. The current design of the IAAAP 155 round manufacturing process is inefficient, since it has yet to fully automate the manufacturing line, and the automated portions have large cages around them to prevent the actuators from injuring someone or something. Fig. 6 depicts the system integration.

The novel nature of this project is the torque and vision safety. The passive safety of the gripper design is used throughout manufacturing lines, and the computer vision used to detect rounds is likewise commonplace. However, measuring the current used by an individual actuator, then mapping that to the torque produced by the actuator to determine whether the arm has experienced a collision is not commonly used in industry. If it were, there would be no need for cages around automated portions

Fig. 5. CAD Graphic (top) and image (bottom) of Threaded Gripper Design

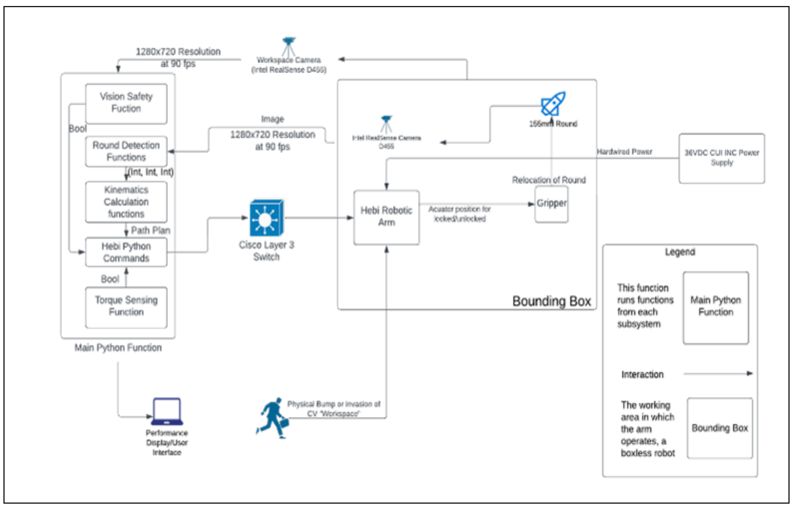

Fig. 6. Block diagram depicting multi-tiered safety subsystems

of a manufacturing line. Likewise, computer vision safety is not commonly used, although relatively easy to implement. The combination of torque and vision safety could drastically increase the effectiveness of a manufacturing line, since the current use of cages surrounding automated portions decreases the usable area for the manufacturing floor.

As depicted in Fig. 6, WAR integrated all subsystems into a singular file directory capable of performing all necessary operations and calculations. As such, the performance display is really just a display, and we no longer have any shared text files. The Round Detection and Kinematics calculations run continuously, and when a torque or workspace violation occurs, a Boolean variable changes. The Boolean is an input of the function used to command the arm. If it is true, then the arm stops all movement. Thus, the camera serves two functions, both determining the location of the round, as well as detecting motion in the immediate vicinity of the arm. The round detection functions return the XYZ coordinates of the next round to be picked up in the robotic arm's coordinate system. The motion detection algorithm is theoretically used to monitor movement around the arm, excluding the movement of the actual arm. The Kinematics function calculates an appropriate path for the arm to move between the current and desired positions of the round, and the waypoints of that path are fed to the HEBI trajectories function from the API used to command the arm.

V. Results

A. Kinematics Testing

To date, a series of tests have been conducted in nearly all areas of research. The dynamic path planning requires inverse kinematics. Previously, this was done using proprietary software. Proprietary software does not serve the mission to provide partners at IAAAP with a novel design to move 155 rounds. Therefore, the project has transitioned to Python 3, an open-source programming language to ensure that IAAAP can utilize our final product. Although there is a library for Python which offers an inverse kinematics function, it does not accurately move the arm. The team has chosen to instead use the center of inertia of each component to determine the inverse kinematics using Jacobian matrices, iterating through arms with increasing degrees of freedom. So far, the team successfully developed inverse kinematics scripts for 2-DOF, 3-DOF, and 6-DOF arms. This was conducted by developing and programming the proper relations between body fixed reference frames, accounting for mass, length, and center of inertia. After developing a script capable of calculating the inverse kinematics, two three-dimensional points in the cartesian reference frame were chosen, and the arms movement between them is monitored. Since the arm is successfully able to move between the two points with minimal error and achieve a steady state error of zero at the final end effector position, the test is considered a success. Fig. 7 shows verification of calculations for the kinematics, and path planning. Before being sent to the actuators, the commands are verified with an accuracy of micrometers to the desired XYZ locations.

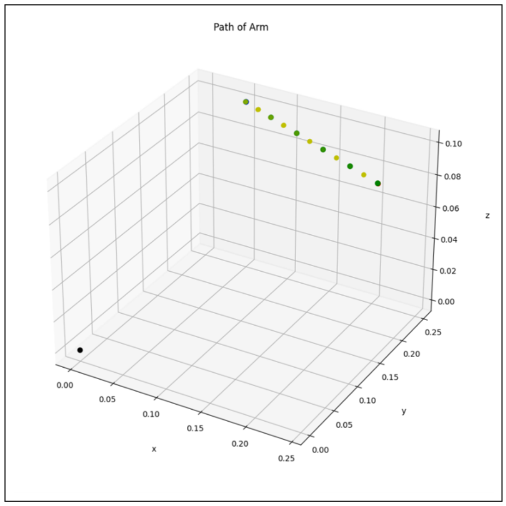

Fig. 7. Plot of Straight-Line trajectory

B. Gripper Testing

Another development in the project which required testing is the passive safety of the gripper. The previous gripper failed if the arm lost power and would drop the rounds. As a result, the gripper was designed to utilize springs to ensure that the gripper's threads more efficiently interlock with the threads of the round passively 5. The specific thread design was provided and specified by IAAAP to ensure compatibility. The springs used to passively expand the gripper are not expected to be a point of failure, since they are not a significant load-bearing part. Since the new gripper design can lift and release rounds without dropping them when power is lost, the the test is considered a success. Furthermore, the gripper's threads and springs were visually inspected for deformation and strain after continuous use, and did not have any degradation which would indicate loss of structural integrity. Although the gripper did not show signs of fatigue, no test was conducted to determine the total fatigue life. The grippers currently in use at IAAAP have a fatigue life of approximately 1000 rounds before they are replaced, which is a reasonable expectation for this gripper, since the point of failure is still the threads.

C. Computer Vision Testing

The team has made progress on the computer vision aspect of the project. The algorithm from previous years falsely identified the motors on the arm as rounds, which would stop the arm's movement. To prevent this, the team has developed a depth sensing capability, and screens out all false positives not at the proper depth. Since the slope of a round is a known and fixed value, if an object is identified, but it does not have the proper slope, it is be dismissed. To test the computer vision, the camera mapped the change in depth of all identified objects, and if the object does not have the proper gradient, it is not considered to be a round. Circular objects such as steel samples, balls, and water bottles were used, and since the camera is able to successfully identify the round in the environment with false positives, the test was considered successful.

D. Torque Safety Testing

The team has successfully conducted a torque safety test with a 2-DOF, 3-DOF, and 6-DOF arm. The torque test is conducted by calculating the torque required by each individual motor to move the arm. If the torque exerted by a motor is significantly more than the calculated value, the arm has struck an obstacle, and needs to stop. This test is conducted in phases. First, the arm moved continuously following an arbitrary sinusoidal path. When the arm struck an object, it stopped. This test was repeated with increasing degrees of freedom until a 6-DOF arm was used and tested under similar conditions. If any of the modular motors detect a torque which exceeded the calculated torque, the arm stopped. Then, the test was conducted using inverse kinematics with a 6-DOF arm, rather than an arbitrary path. Again, if the arm struck an object, it stopped. The force exerted by the arm on an object was calculated from the torque the arm applied over the time until the arm stopped, and the test was considered a success since the impulse of the arm is less than the impulse required to cause a human harm. This test was conducted with the 6-DOF arm which was found to be effective if the collision occurred at a point sufficiently far from the actuator being tested. However, if the collision occurred at an actuator or near the base of the actuator, there was not a significant measured increase in torque and therefore that actuator would not trigger the safety threshold. Another actuator in the arm may detect the collision but did not in all instances.

E. Cybersecurity Testing

To test the cyber security of our system, an ethernet connection was used to connect a new computer to the switch which attempted to take control of the arm. Since the switch was secure, any computer with an unrecognized MAC address was unable to send packets to the arm. Similarly, the switch obstructed all packets that were not transmitted using UDP.

F. Subsystem Integration Test Plan

This test was a demonstration of the arm moving to a given 3-dimensional coordinate determined with round detection while using torque and vision safety. This demonstrated integration of the computer vision and kinematics functionalities communicating between each subsystem. The demonstration was done live to show how the arm reacts to live updates in the position of the rounds and the straight-line distances it must traverse to move the round from one position to another. A computer simulation of such a movement is shown in Fig. 8. During the demonstration, the arm was able to accurately detect a round, move to the initial location of the round with varied success, and drop the round at the final location while constantly monitoring torque. Vision safety, past the extent of round detection, was not integrated into the final project.

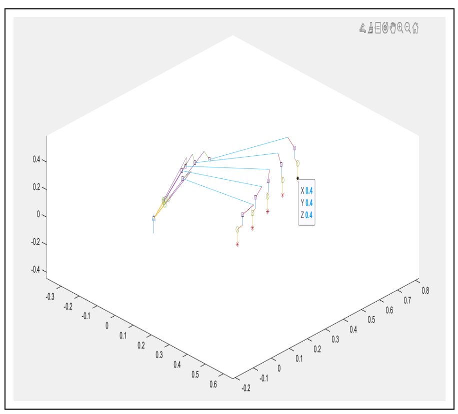

Fig. 8. Demonstration of Robotic Arm movement

VI. Conclusion and Future Work

The adoption of autonomous robots in the manufacturing sector has the potential to transform the economics of the industry, and to redistribute human resources in a way that will lead to safer workplaces, reduced waste, reduced operational costs, increased precision, and the creation of more desirable jobs. This will indirectly contribute to the betterment of humanity in the areas of improved consumer safety, increased quality of life, and increased labor output. With the added benefit of multi-tiered safety features and dynamic path planning/task deconfliction, the manufacturing industry can seamlessly incorporate the ingenuity of human workers with the precision of autonomous robots without fear of hazardous working conditions. Ultimately, WAR plans to scale up to industrial grade arms and eventually publish findings in prominent engineering journals as well as document our work and disseminate it broadly through partnerships within the DoD and prominent civilian tech industries.

It is import to consider that although a robotic arm with 6DOF offers virtually limitless control, it is expensive and inefficient. Since the weight of the object being lifted is applied as a torque through all modules, the base needs to be sufficiently strong, else the arm is unable to lift the object. The linear torque applied through the modules requires the modules closer to the base to have significantly more power. We propose the adoption of a FANUC industrial robot for future iterations of this research project.

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Appendix A
Detailed Design Specifications

6DOF Arm

- Source code must be written entirely in Python for all subsystems.
- Constructed using 6 daisy-chained HEBI X-Series Actuators.
- Commanded via wired ethernet connection between computer, router, and arm.
- Powered with 24-48V DC.
- Payload of at 40 pounds.

Dynamic Path Planning Algorithm

- Dynamically calculates a trajectory using a numerical solution to the inverse kinematics problem.
- Calculations converge to a desired coordinate with an accuracy of 0.01 radians per gimbal, and an accuracy of 0.005 meters to a desired coordinate within the arm's own coordinate frame (even if it does not correlate with the camera's coordinate frame)
- Receives Cartesian coordinate information from computer vision subsystem.
- Moves at a constant adjustable (via GUI) velocity between any two fixed points. Fig. 9
- Receives drop off coordinate from GUI subsystem

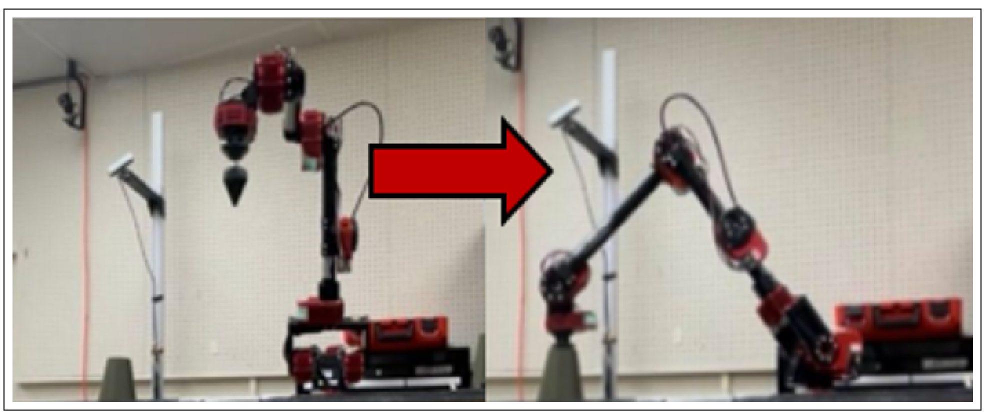

Fig. 9. Dynamic movement of 6DOF arm

Vision Safety

- Maintain a constant coordinate system that can be translated and rotated to match the robot arm's coordinate frame.
- Sends live camera feed to GUI.
- Accurate detection of the center of the cut off rounds within 10 mm tolerance.
- Must use Intel RealSense cameras or cameras compatible with computer vision Python libraries like OpenCV.

Torque Safety

- Calculates static torque with and without a round as a baseline.
- Calculates the expected torque to within .1 N-m.
- Measures the actual torque to within .1 N-m.
- Stops the arm within .1 s if the actual torque exceeds the expected torque.
- Sends live torque plot to GUI.

Gripper Design

- Utilizes geometry of threaded 155 rounds to interface with threaded gripper.
- Does not have any pinch point hazards or sharp edges.

- Has a life cycle of at least half a month, the current life cycle at IAAAP.
- Holds round without being actively powered.
- Made of ABS plastic (printed with CNC machine) and reinforced with a steel core.
- Tolerance of .005 inches to ensure threads align.

Cybersecurity

- Main computer (master node) must be able to communicate with all other subsystems.
- Additional computers on the network should not be able to communicate with the arm or view network traffic.
- Only robot commands and feedback messages are allowed on the network.
- Air-gapped

Graphic User Interface (GUI)

- Main tab with live camera feed, live torque plotting, and live round location, and calculated trajectory of end effector. Fig. 10
- Settings tab allowing user to edit desired drop off coordinates, movement speed, and other relevant settings.

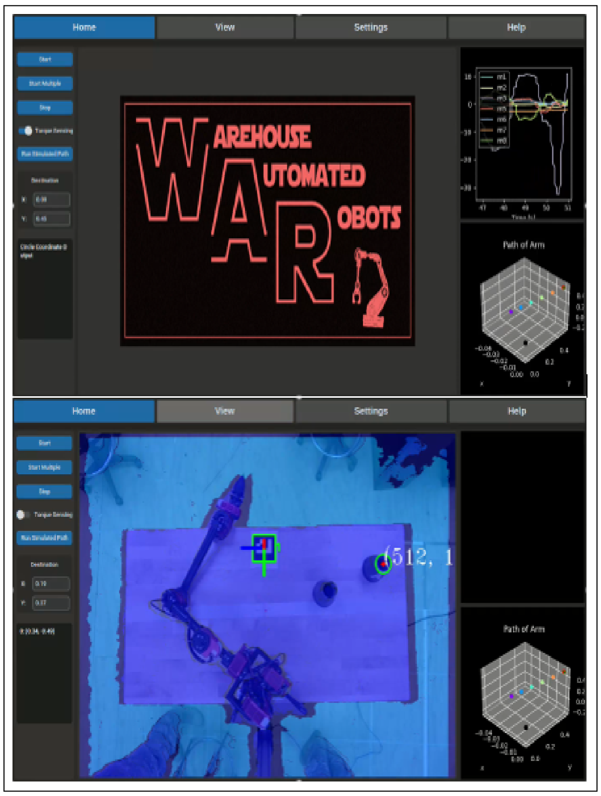

Fig. 10. GUI displaying live torque plotting (top) and live camera feed (bottom)