# Abstract

# Introduction

Maritime RobotX Challenge 2022 consists of various autonomous challenges with an emphasis on science and cooperative autonomy. For RobotX 2022, teams are assigned to an Unmanned surface vehicle (USV) and are required 9 tasks. Tasks include Situational Awareness and reporting, detection of an underwater Pinger, navigation within buoys, detection and classification of hyperspectral images, detection of color and sequence, detection of colour and docking, find and object delivery, UAV replenishment, UAV search and report.

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| Figure 2A: USV Heartbeat | Figure 2B: Exit and Entrance | Figure 2C: Follow the path |
| Figure 1D: React and Report | Figure 2E: Scan the Code | Figure 2F: Detect and Dock |
| Figure 2G: Find and Fling | Figure 2H: UAV Replenishment | Figure 2I: UAV Search and Report |

The project is split into functional groups where various team members are responsible for handling of certain tasks. In this report, emphasis will be focused on Find and Fling. Figure 2J and Table 2A shows the detailed specification of the mission.

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| Diagram  Description automatically generated  Figure 2J: Detailed layout of mission |
| Table 2A: Task Elements for Find and Fling |

The task requires a racquetball to be delivered to the desired coloured window, where delivering to the smaller window results in higher points. As the mission is fully autonomous, the design and control of an intelligent agent is required. Agents are things that sense and act on the environment. The environment the system operates in is a Partially Observable, Stochastic, Collaborative, Multi-agent, Dynamic, and Continuous environment. Hence, the agent must be a goal-based, utility agent. Where the goal is to deliver the racquetball and the utility is to minimize the travelled path.

To complete the task, perception, mobility, and manipulation are required. Perception allows the system to sense surrounding to decide the next course of action. Mobility is the ability to transport objects across distances. Manipulation refers to interaction between robotic arms and objects grasping objects, opening doors, tightening screws etc.

For mobility 3 main methodologies are available. They are propelling, flinging, and delivering a projectile.

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| Projectiles launched at an angle review (article) | Khan Academy  Figure 3K: Propelling of projectile [1] | TossingBot: Learning to Throw Arbitrary Objects with Residual Physics  Figure 2L: TossingBot [2] | Industrial robots  Figure 2M: Industrial robots [3] |

For propulsion of projectile, compressed gas, chemical reaction, springs or spinning wheels are used for rapid acceleration. For tossing, TossingBot using a deep reinforcement learning model to train the robotic arm to deliver objects. Compared to projectile motion, this allows objects of various shapes to be delivered with a single system[4]. Additionally, projectile range would an extension to the arm’s workspace. Lastly, robotic arms contain precise actuators designed to grab and deliver objects to anywhere within its workspace. The first two methods of delivery revolve around the field of fluid dynamics as the projectile is heavily influenced by environmental conditions such as wind. Specifically, the trajectory will be of projectile motion with drag governed by the Magnus effect with disturbances. Whereas robotic arms could provide a solution of higher accuracy as the robotic arm reaches to the window to release the racquetball. For the first 2 methods, the delivery system is an open loop system where the system has no control of the trajectory once the ball leaves the actuators. The direct delivery of objects results in a closed loop system allowing a controlled system.

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| Figure 2N: Magnus Effect from rotation and drag[5] | Open Loop and Closed Loop Animation - Inst Tools  Figure 2O: Open vs Closed Loop System [6] | This is not the workspace of the Meca500 robot  Figure 2P: Workspace of Meca500 robot [7] |

Previous competition has focused on propelling balls such as designs in [8], [9], [10]. Which aims to launch the balls into the target position through projectile motion. Using compressed air or ball accelerators, the system is bulky, heavy, and expensive. Hence there is an opportunity to improve the methodology of object delivery.

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| Figure 2Q: Bumblebee Projectile [8] | Figure 2R: NaviGatorUF Projectile[9] | Figure 2S: UON USV [9],[11] |

In addition to robotic arms, Unmanned Aerial Vehicles (UAVs) could be used to deliver the payload. Compared to robotic arms, UAVs can be much cheaper and lighter. Robotic arms increase in costs as the distance between the base and the end effector increases. This effect is due to square cube law where the increase in length result in a cubic proportional weight increase [12]. Resulting in larger bases and stronger motors to support the end effector. UAVs are underactuated 6 DOF bodies where their configuration space is not limited by distance but battery and telemetry signal. This makes UAVs extremely attractive for delivery of payload over large distances.

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| Work more efficiently with a power law - deparkes  Figure 2T: Square Cube Law [12] | servomotor - Robotic arm select servo motors - Robotics Stack Exchange  Figure 2U: Sizing of Robotic Arm [13] | The movements are based on the speed of each rotor: (a) If all rotors spin at the same speed, the quadcopter will move upward. (b) If the speed of two rotors spinning in the same direction is higher than the speed of the others, the quadcopter will rotate on the Y-axis. (c) and (d). If two rotors spinning in the same direction rotate   Figure 2V: Underactuated 6DOF UAV [14] |

Therefore, this project explores the possibility of a robotic arm design targeting object delivery. The design includes perception, mobility, and manipulation for the object to be delivered. Whereby the robotic arm would be able to pick objects and deliver the payload in an autonomous fashion accurately. Sensors and methodologies for perception and different types of robotic arms/UAVs would be evaluated, resulting in the best design suitable for RobotX’s challenge.

# Literature Review

# Robotic Arms

Industry 3.0 has led to the rapid development of Robotic Arms which have been integrated to factories to automate processes. Companies such as ABB, Fanuc and KUKA have been developing products for industry purposes [15]–[17].

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| Figure 3A: ABB Robotic Arm[15] | Figure 3B: FANUC Robotic Arm[16] | Figure 3C: KUKA Robotic Arm[17] |

Typical industrial arms have 6 actuators resulting in a 6 degree of freedom (DOF) arm, allowing end effectors to reach anywhere within the arm’s workspace at any angle. Any increase in DOF will result in kinematic redundant arm. Where multiple solution exists for the end effector to reach desired space and orientation [18]. To reach a desired point and orientation of the end effector in space, a robotics study, inverse kinematics (IK) is used to calculate desired joint angles for the actuators. This is done by solving the forward kinematics problem (FK) and the inverting it to find a solution. To solve the problem there are 2 approaches, analytical and numerical. Traditionally, Denavit-Hartenberg (DH) parameters are used describe a body. DH parameters are generated based on a fixed convention. The steps to generate DH parameters are as follows.

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| Steps to generate Coordinate system: |
| 1. Let axis *i* be numbers axis of joints connecting link *i*-1 to *i*. |
| 1. Set *Zi* to be the axis of rotation or translation of the joint. The direction is arbitrary. |
| 1. Set the origin, *Oi* at the intersect of axis *Zi* with the common normal of *Zi-1* and *Zi* |
| 1. Set *O’i on Zi at the intersect of* common normal of *Zi* and *Zi+1* |
| 1. Select axis *Xi* along the common normal to axes *Zi-1* and *Zi* from former |
| 1. Set axis *Yi* using right hand grip rule. |
| Additional Notes: |
| 1. For Link 0, only direction of *Z1* is specified. *Oi* and *Xi* can be chosen arbitrary. |
| 1. When two consecutive axes are parallel, the common normal is not uniquely defined. |
| 1. When two consecutive axes intersect, the direction of *X1* is arbitrary. |
| 1. If the joint is prismatic, the direction of *Zi* is determined and *Oi* is arbitrary. |
| Parameters for table |
| 1. θ*i* (Joint Angle) Angle between *Xi* and *Xi+1* about axis *Zi+1* |
| 1. α*i* (Twist Angle) Angle between *Zi* and *Zi+1* about axis *Xi+1* |
| 1. r*i* (Link Length) Length between *O’i* and *Oi +1* |
| 1. d*i* (Joint Offset)Length between *Xi* and *Xi+1* about axis *Zi+1* |

Next, the values from the DH table are used to generate transformation matrices to describe the relationships between the bodies. This matrix would be used for inverse kinematics.

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| kinematics - Denavit-hartenberg parameters sign 6-DOF - Robotics Stack  Exchange  Figure 3D: ABB IRB 7600 with coordinate system [19] | |  |  |  |  |  | | --- | --- | --- | --- | --- | | Joint *i* | θ*i* (deg) | α*i* (deg) | r*i* (cm) | d*i* (cm) | | 1 | 0 | -90 | 0.41 | 0.78 | | 2 | -90 | 0 | 1.075 | 0 | | 3 | 0 | -90 | 0.165 | 0 | | 4 | 0 | -0 | 0 | 1.056 | | 5 | 0 | -90 | 0 | 0 | | 6 | 180 | 0 | 0 | 0.25 |   *Table 3A: ABB IRB 7600 Table for DH parameters* [19] |

*Equations for DH transformation Matrix for Forward Kinematics*

Once the calculations have been completed by providing a designed position and orientation, the system of linear equations can be solved to produce the various joint angles. However, with by solving the system of linear equation, multiple or no solutions may exist.

In comparison to analytical solutions, numerical solutions provide an alternative to avoid the possibility of an empty solution space. This is accomplished by iterative optimization to find an approximate solution, bypassing the difficulty of inverting the FK equation. Methods include Jacobian inverse technique which is solving the problem in the form of a taylor series expansion or heuristic methods to iterate joint angles to minimize the error between the end effector and desired position. These heuristic methods include cyclic coordinate descent (CCD) and forward and backward reaching inverse kinematics (FABRIK).

To complete Jacobian inverse numerical analysis, the following equations are used.

By initialising a suitable step size, h, the is iterated till it converges till < , where is a small error tolerance defined by the user [20].

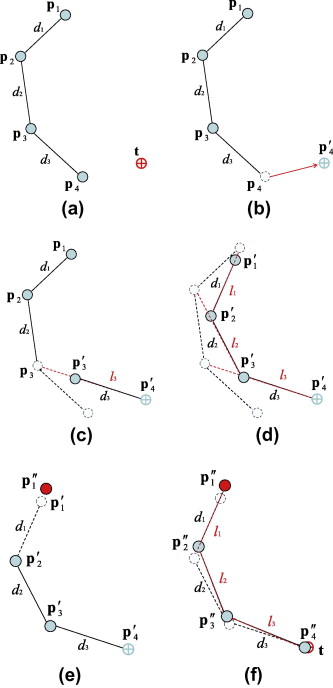


Figure 3E: Visualisation of FABRIK process

In addition to solving IK using DH parameters, the Unified Robot Description Format (URDF) has gained popularity as it contains more parameters. A URDF is an XML file and is especially popular with Robotics Operating System (ROS) users. URDF files contain elements like <links>, <joint> , <inertial> and many other elements. These elements can be loaded into simulators such as Gazebo or Pybullet, which could simulate the environment and forces while solving inverse kinematics equations. An example UDRF file is as follows.

A black and white document

Description automatically generated with medium confidence

Figure 3F: XML URDF file

A screenshot of a computer

Description automatically generated with medium confidence

Figure 3G: Simulation of URDF model with varied joint angles

# Unmanned Aerial Vehicle

By implementing an UAV to deliver the projectile, the workspace of the UAV can be greatly extended resulting in a long range, full 6 DOF system. Generally, there are 4 categories of UAVs. The drones consist of a flight controller where it collects data from the inertia measurement unit (IMU) and performs sensor fusion while applying Extended Kalman Filter (EKF), reducing noise. Control theory is then used to model the flight dynamics and a PID controller is used to maintain stability. Figure 3F show the various categories of UAVs.

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| What Is A PID Controller And How It Works? - PLCynergy  Figure 3F: PID Controller [21] | Diagram  Description automatically generated  Figure 3G: Categories of UAVs [22] |

While fixed-wing UAVs have better flight efficiency, multi-rotor drones are selected due to the lower cost and better maneuverability. Fixed-wing UAVs require a runway to take off and have a much larger turning radius which would impede the performance of payload delivery. This is so as the UAV is unable to hover in place, resulting in the moment delivery of the payload.

Ardupilot is an open-source autopilot system where various configuration of autonomous systems are supported. Firmware for Rovers, fixed wing plants multi rotors and copters are supported.

Graphical user interface, application

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Figure 3H: Firmwares for various autonomous devices

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To connect to a companion computer, MAVROS, a ROS package could be installed where the computer would be able to communicate with the flight controller over MAVLink. Where MAVLink is a messaging protocol where commands can be sent, and parameters can be received. This allows the standalone UAV to act as a goal-based agent where location data (state) can be stored and saved on the companion computer.

# Proposed Design

The first proposed design consists of a 5DOF robotic arm modelled on SolidWorks. The robotic arm consists of 6 links and 5 joints, where the final link is the end effector. The robotic arm is a 1:6 scaled down model. The actuators used are servo motors, MG996R and SG90.

Diagram

Description automatically generated

# References

[1] “Projectiles launched at an angle review (article) | Khan Academy.” https://www.khanacademy.org/science/in-in-class11th-physics/in-in-class11th-physics-motion-in-a-plane/projectiles-launched-at-an-angle/a/projectiles-launched-at-angles (accessed Feb. 27, 2022).

[2] A. Zeng, S. Song, J. Lee, A. Rodriguez, and T. Funkhouser, “TossingBot: Learning to Throw Arbitrary Objects with Residual Physics,” *IEEE Transactions on Robotics*, vol. 36, no. 4, pp. 1307–1319, Aug. 2020, doi: 10.1109/TRO.2020.2988642.

[3] “RobotWorx - Industrial Robot History.” https://www.robots.com/articles/industrial-robot-history (accessed Feb. 27, 2022).

[4] A. Zeng, S. Song, J. Lee, A. Rodriguez, and T. Funkhouser, “IEEE TRANSACTIONS ON ROBOTICS 1 TossingBot: Learning to Throw Arbitrary Objects with Residual Physics”, Accessed: Feb. 27, 2022. [Online]. Available: http://tossingbot.cs.princeton.eduhttp://tossingbot.cs.princeton.edu

[5] K. Wójcicki and K. Puciłowski, “Zbigniew Kulesza Mathematical Analysis for a New Tennis Ball Launcher”.

[6] “Open Loop and Closed Loop Animation - Inst Tools.” https://instrumentationtools.com/open-loop-and-closed-loop-animation/ (accessed Feb. 28, 2022).

[7] “What is the workspace of a typical six‑axis industrial robot arm?” https://www.mecademic.com/en/what-is-the-workspace-of-a-typical-six-axis-industrial-robot-arm (accessed Feb. 28, 2022).

[8] “boat-latest-png.png (PNG Image, 1400 × 663 pixels) — Scaled (91%).” https://bumblebee.sg/img/boat-latest-png.png (accessed Feb. 28, 2022).

[9] “NaviGator.” http://navigatoruf.org/ (accessed Feb. 28, 2022).

[10] J. Courts, J. Franklin, M. Kete, D. Hirst, J. Arens, and S. Burt, “UoN RobotX 2018 Technical Paper”.

[11] “Blog – UON RobotX.” https://uonrobotx.wordpress.com/blog/#jp-carousel-92 (accessed Feb. 28, 2022).

[12] “Work more efficiently with a power law - deparkes.” https://deparkes.co.uk/2014/07/14/how-a-power-law-can-help-you-work-more-efficiently/ (accessed Feb. 28, 2022).

[13] “servomotor - Robotic arm select servo motors - Robotics Stack Exchange.” https://robotics.stackexchange.com/questions/14504/robotic-arm-select-servo-motors (accessed Feb. 28, 2022).

[14] “The movements are based on the speed of each rotor: (a) If all rotors... | Download Scientific Diagram.” https://www.researchgate.net/figure/The-movements-are-based-on-the-speed-of-each-rotor-a-If-all-rotors-spin-at-the-same\_fig1\_316609149 (accessed Feb. 28, 2022).

[15] “ABB Manipulators.” https://robots.ros.org/abb-manipulators/ (accessed Feb. 28, 2022).

[16] “Fanuc.” https://robots.ros.org/fanuc/ (accessed Feb. 28, 2022).

[17] “25% of KUKA shares trade hands - The Robot Report.” https://www.therobotreport.com/25-of-kuka-shares-trade-hands/ (accessed Feb. 28, 2022).

[18] “What are the six degrees of freedom in a robot arm? – Marginally Clever Robots.” https://www.marginallyclever.com/2014/02/what-are-the-six-degrees-of-freedom-in-a-robot-arm/ (accessed Feb. 28, 2022).

[19] “kinematics - Denavit-hartenberg parameters sign 6-DOF - Robotics Stack Exchange.” https://robotics.stackexchange.com/questions/21559/denavit-hartenberg-parameters-sign-6-dof (accessed Mar. 01, 2022).

[20] “Overview of Jacobian IK. What is the math behind Jacobian IK… | by Luis Bermudez | Unity3DAnimation | Medium.” https://medium.com/unity3danimation/overview-of-jacobian-ik-a33939639ab2 (accessed Mar. 01, 2022).

[21] “What Is A PID Controller And How It Works? - PLCynergy.” https://plcynergy.com/pid-controller/ (accessed Mar. 01, 2022).

[22] M. Javaid, I. H. Khan, R. P. Singh, S. Rab, and R. Suman, “Exploring contributions of drones towards Industry 4.0,” *Industrial Robot*, 2021, doi: 10.1108/IR-09-2021-0203/FULL/PDF.