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Collaborative Dual-Arm Robot System for Aircraft Ground Refuelling

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***Abstract*— The growing demand for automation, alongside advancements in robotics, sensing, and artificial intelligence, is driving the adoption of professional service robots across multiple sectors. In the aerospace industry, aircraft ground refuelling remains a hazardous, labour-intensive task with significant potential for robotic automation. Despite decades of interest, autonomous refuelling has yet to be realised due to the complexity of the environment, technical challenges in nozzle manipulation, and limitations of legacy robotic systems. This paper presents a novel collaborative closed-loop kinematic chain robot for autonomous fuel nozzle positioning and latching. The system addresses key challenges such as accurate fuel port localisation, precise nozzle manipulation and positioning, and secure connection, all within a semi-structured airport environment. A robot demonstrator was developed as part of an industry-funded project aimed to demonstrate the solution's potential to enhance safety and improve efficiency in commercial aircraft refuelling.**

Keywords—Aviation MRO, autonomous manufacturing, robotics, aircraft refuelling, close-loop kinematic chain, dual-arm robot

I. Introduction

The professional service robotics sector is experiencing significant growth, driven by increasing demands for automation and advances in robotics, sensing technologies, and artificial intelligence. Robots are now being employed across diverse sectors, including agriculture, logistics, healthcare, and customer service. The aerospace industry offers substantial opportunities for the deployment of robotic and automation technologies due to its inherently harsh working conditions, ergonomic challenges, and stringent health and safety requirements. Despite this potential, the industry has struggled to adopt robotic automation effectively.

Automating airport operations presents numerous challenges due to the complexity of the environment, the need for seamless integration with existing infrastructure, and the potential impact on the workforce. Airports are dynamic and highly interconnected systems where each component must function efficiently, often under unpredictable conditions. Commercial aircraft refuelling is a critical operation within this domain, and its inherent difficulties make it a prime candidate for automation. Key challenges include the precise manipulation and positioning of the fuel nozzle, secure mating and latching with the aircraft's fuel port, and operation within semi-structured, manual working environments.

Robotic aircraft ground refuelling represents a significant research challenge in the field of robotics, aiming to automate a complex and hazardous manual task within the aerospace sector. This process involves considerable fire risk due to the presence of flammable liquids and vapours, as well as dynamic environmental conditions [1], [2]. Manual refuelling operations are further complicated by human factors such as repetitive handling of heavy equipment, working at height, and assuming awkward postures [3]. Autonomous robotic refuelling systems have the potential to mitigate these risks by removing human operators from hazardous zones, improving operational safety, enhancing efficiency, and reducing operating costs [4].

The concept of robotic aircraft refuelling has been explored since the 1980s [5]. However, technical complexity and limitations in robotics and sensing technologies have historically prevented its realisation. On the other hand, robotic refuelling has been explored in various domains, including road vehicle refuelling [8], marine vehicle refuelling [9], and spacecraft refuelling [10]. An autonomous refuelling robot must accurately detect and localise the aircraft's fuel port and precisely position the fuel nozzle to achieve a secure connection. The standardised design of fuel nozzles and ports, optimised for manual operation, requires the nozzle to be inserted and twisted within the port to form a proper seal. While existing research has addressed vision-based detection and localisation of fuel ports [6], [7], the robotic manipulation and precise positioning of the fuel nozzle remains an underexplored area.

This paper presents a novel collaborative dual-arm robot design for fuel nozzle positioning and latching in autonomous aircraft refuelling. The system was developed as part of an industry-funded project and demonstrated at Technology

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Readiness Level (TRL) 4 using an Airbus A320 wing and fuel port.

II. System concept

A. System overview

The developed system consists of two Universal Robot UR5 collaborative robots integrated with a mobile platform. Each robot is mounted at the top of a pillar on each end of the platform. The mobile platform has a rigid ladder frame chassis with four wheels that provides the demonstrator mobility to support moving between indoor hanger and outdoor representative testing environments. The end-effector flanges of the two robots are connected using a shared tool flange via bearings 3D printed using soft PLA, as illustrated in Fig. 1, which provide an additional passive joint that rotates around the 6th joint z-axis of each robot with some compliance. The two robot controllers are positioned between the robot arms and below the robot bases to maintain a low centre of gravity. A 347GF Cla-Val fuel nozzle is attached to the middle of the interface using two bolts. This is a standardised fuel nozzle that is applicable to most commercial aircraft. The robot arms share the same TCP at the centre of the fuel nozzle tip. The robot system is programmed and controlled using RoboDK.

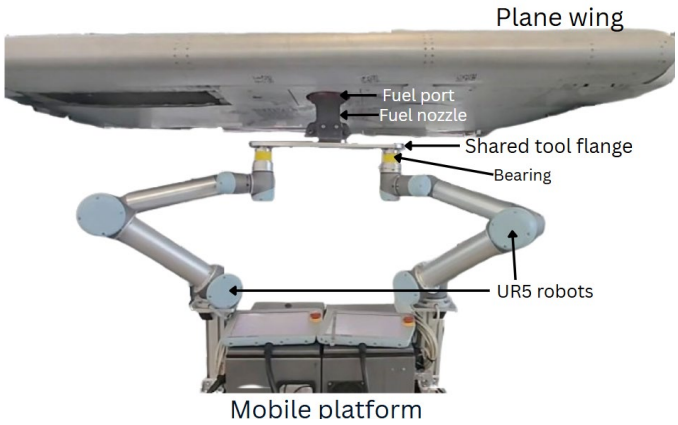

Fig. 1. Mobile dual-robot refuelling system setup.

B. Design Rationale

Aircraft ground refuelling is currently performed manually by airport personnel, who connect the fuel nozzle from a refuelling truck to the aircraft. This task requires a two-handed operation due to the significant weight of the fuel nozzle and the high positional accuracy needed to latch it securely onto the aircraft's refuelling port.

The initial system design employs a Universal Robots UR16e collaborative robot, which has a payload capacity of 16 kg. In preliminary trials, the robot was equipped with an actual fuel nozzle as shown in Fig. 2, aligned such that the z-axis of the nozzle matched the robot's tool flange to simulate latching onto the Airbus A320 refuelling port. A program developed in URScript was used to drive the robot to insert the nozzle into the port and rotate it 90 degrees to latch and lock it in place. While the robot successfully positioned the nozzle, it encountered difficulty during the locking and unlocking phase. This issue stems from the limited torque available in the robot's sixth joint, a common constraint in collaborative robots.

Fig.2. Initial system design using a UR16e robot with nozzle attached.

Although it is theoretically possible to reorient the robot to leverage higher-torque joints for the rotation, doing so may cause damage or reduce the operational lifespan of the smaller joints. An alternative approach is to incorporate a high-torque external axis; however, this would increase the payload demands on the robot and could expose it to damaging reaction forces. A more viable strategy involves the use of mechanical leverage, specifically, attaching an extended handle to the fuel nozzle. This allows the robot to grasp the nozzle at the end of the handle and perform the required rotation with reduced torque. However, this solution shifts the centre of mass away from the robot's Tool Centre Point (TCP), making it unsuitable for most collaborative robots, which typically have payload limits of 20 kg or less. A conventional industrial robot with significantly higher payload will be capable of handling the fuel nozzle and hose on an extended handle, but it will significantly increase the platform payload requirement. A conventional industrial robot will also require an integrated safety monitoring system to ensure safe deployment. Safety monitoring system are required to separate the moving robot from surrounding people, which often hinder the workflow of the surrounding operations.

Using two robots in parallel to share the workload can result in more robust operations while allowing the use of smaller collaborative robot to avoid hazards associated with conventional robots to improve system safety. This paper demonstrates the advantages of the close-loop kinematic chain robot configuration using two small collaborative robots connected.

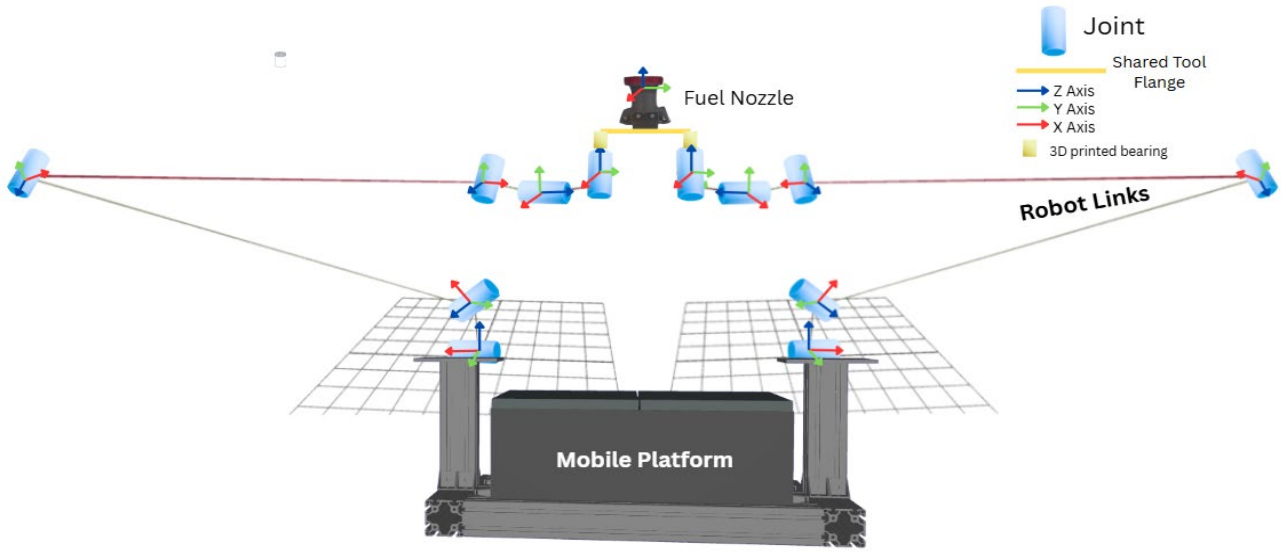

Fig. 3. Kinematics diagram of the refuelling robot system.

C. System kinematics

The system consists of two robot arms mounted 0.78m apart with coinciding base X axes in opposing directions, as shown in the robot system's kinematics diagram in Fig. 3. Each robot arm has 6 rotary joints and 6 DOF. The 6th joints of the robots are connected using a shared tool flange via a passive rotary joint for each robot. The fuel nozzle is mounted rigidly to the middle of the shared tool flange. This resulted in 6 DOF at the TCP.

The identical robot arms in the system share a common TCP. Thus, the Denavit-Hartenberg (DH) parameters in Table 1 can be used to describe both robot arms.

TABLE I. DH TABLE FOR EACH ROBOT ARM

Link	α_i (°)	θ_i offset (°)	a_i (mm)	d_i (mm)
1	90.00	-139.26	0.00	89.20
2	0.00	-32.66	-425.00	0.00
3	0.00	-153.57	-392.00	0.00
4	90.00	-83.21	0.00	109.30
5	-90.00	-90.03	0.00	94.75
6	0.00	139.26	0.00	82.50
Shared tool flange(L)	0.00	θ	225.00	0.00
Shared tool flange(R)	0.00	θ	-225.00	0.00
Fuel Nozzle	0	0	0.00	250

Inverse kinematics (IK) plays a crucial role in computing the joint configurations required to reach the end effector possess during the synchronised motion. Each UR5 robot has 6 DoF, i.e. six joint angles [θ_1, θ_2, θ_3, θ_4, θ_5, θ_6] which are calculated adjusted and modified to achieve a specific tool pose TP in the 3D space.

$$TP = f(\theta) \implies \theta = f^{-1}(TP) \quad (1)$$

f represents the forward kinematics function mapping the joint angles to the transformation matrix T for the tool pose. Cartesian poses for home, target position etc., are expressed using the RoboDK "transl(x, y, z)" and rotation functions like "rotx()" and "roty()" to build the transformation matrix T. RoboDK is then used to internally solve inverse kinematics using analytical approach.

Since 6-DOF manipulators such as the UR5 have kinematic redundancy, inverse kinematics produces many valid joint solutions for the same end-effector posture which were 19 possible poses in this particular orientation. These solutions may vary in elbow position (e.g., elbow-up or elbow-down) or wrist design. To achieve the expected trajectory, IK solver majorly relies on the robot's start position along with the waypoints and movement commands given. For synchronised dual-arm tasks, it is vital that both robots use IK solutions that are not only possible independently but also compatible in terms of time and movement continuity. Any inconsistency such as one robot failing to solve IK, switching configurations in mid-motion, or choosing a path with more joint travel, can result in desynchronisation or trajectory failure. Several conditions were considered to maintain the sync, which are discussed below.

D. Robot working envelope analysis

Each robot has its own base frame ("UR5 L base" and "UR5 R base". The mobile platform base frame is Frame3 in Fig. 4. A user defined frame Frame4 is created in the middle of the two robots at the base level of the robots, it acts as the origin of the shared working envelope.

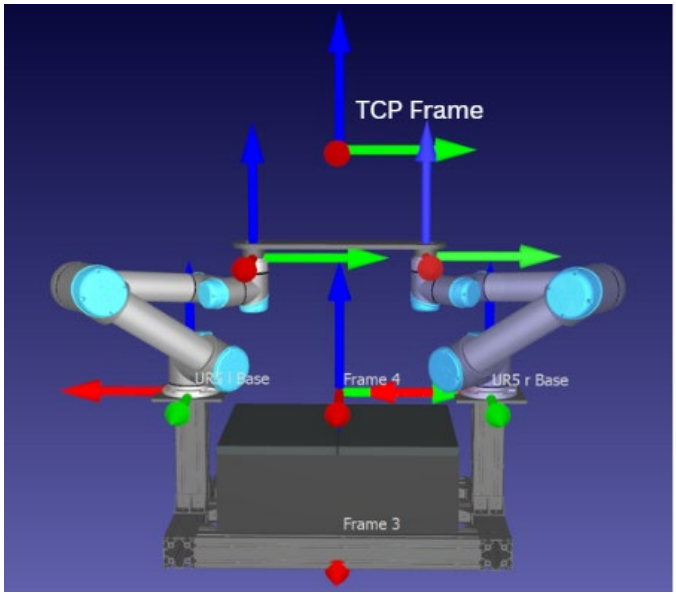

Fig. 4. Robot simulation in RoboDK with key frames of reference.

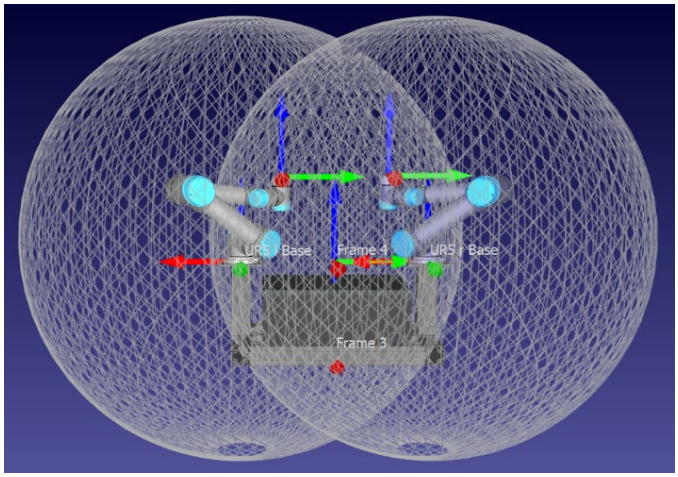

Fig. 5. Working envelopes of the two robot arms.

Fig. 5 shows the working envelope of the two robot arms represented by two semi-transparent spherical meshes. These envelopes are based on the UR5's kinematic capabilities, which account for joint restrictions and mechanical constraints. As our robotic arms share a tool flange it restricts the motion of the two robots to the overlapping region between the robots, hence it becomes crucial to find and work within the shared envelope.

Overall, by linking both the robot base frames with the user defined frame (Frame 4) within the shared envelope allows the system to coordinate properly using homogenous matrices. It also helps in maintaining the sync between the two robotic arms as the waypoints on both the arms is wrt shared frame of reference.

E. Robot synchronisation

After pose calculation using the IK solver, commands like "MoveL" and "MoveC" are used to reach those exact poses. Synchronisation was critical for this movement as unsynchronised arm motions can not only cause collisions, task failure, and system instability but also trigger protective stops instantly. Hence both the arms move in symmetrical and complimentary directions, mimicking human-arm like motion to perform the same task.

The developed system uses a central control framework and external controls for synchronisation but in order to streamline the algorithm synchronisation was achieved by sending non-blocking movement orders (blocking=False) to each robot, followed by WaitFinished() commands. These conditions guarantees that both arms begin their motion with little delay and only go on to the next waypoint after both have completed the current motion.

By performing inverse kinematics (IK) calculations for $\theta_{1\text{-}6}$ for the needed waypoints prior to starting the motion loop, the latency between robot movements was dramatically decreased to a maximum of 54,013.900 µs (about 0.05 seconds). This optimisation significantly enhanced synchronisation between the two robots. Initially, a 1.57-second delay was noticed between their movements, resulting in unsynchronised behaviour and frequent precautionary pauses. This difficulty was efficiently solved by pre-calculating the IK values, resulting in a smoother, more coordinated process.

III. Testing and Demonstration

The dual-arm system further highlighted the need of symmetric path design in reducing relative delays. Even with little software-induced delay, changes in joint travel distance or wrist orientation caused execution lag. To solve this, posture symmetry and joint trajectory matching were constantly monitored, and all MoveL and MoveC commands were intended to have almost equal time-to-completion under the specified speed and acceleration. Although RoboDK does not support hard-synchronised motions (unlike real-time robot controllers), careful use of asynchronous command initiation (blocking=False) and immediate WaitFinished() helped enforce near-parallel execution. To determine the feasibility of the robotic arm framework was subjected to extensive testing and demonstrations in a virtual RoboDK environment as well as real life.

A. Simulation

The major goal for this phase was to test real-time coordination between both arms especially while executing cartesian (MoveL) and circular (MoveC) movements with negligible delays. This led to a full analysis of trajectory planning reliability, inverse kinematics possibility, execution predictability, and synchronised consistency for multiple motion cycles.

As discussed above both the robotic arms were linked to the same virtual reference frame. This calibration ensured that the world coordinate systems for both manipulators remained precisely aligned, avoiding positional discrepancies in trajectory planning. The robots were set to identical speed and acceleration settings (linear speed: 50 mm/s, joint speed: 10 deg/s, acceleration: 100 deg/s²), resulting in precise motion planning and eliminating velocity variance as a source of asynchrony. Collision detection was kept on during the whole testing to replicate real world conditions.

To assess reliability, test runs of the whole motion cycle were performed, including: (1) coming to home, (2) vertical lift, (3) higher lift, (4) circular arc travel to target, (5) circular return to start, and (6) final drop to home position. In all valid runs, both robots completed their courses without any IK failures, singularities, or timing discrepancies over 100 µs. This level of consistency indicates that the dual-arm motion architecture was ready for real-world hardware deployment.

When real world testing was done, one factor that was considered later was the curvature of the wing shape. As the wing is higher near the fuselage there is a hight difference of 5mm which was adjusted in the waypoints as well as an angle of 0.07 radians for the curvature of the wing. The height difference at the end of the circular interpolation was also to be discovered about 8.5mm.

The most important instance was performing MoveC circular translation from home to a target location and back, with intermediate waypoints (pose_mid_left, pose_mid_right) designed to be on a planar arc. During the virtual testing the arc maintained for MoveC was 90° but when tried testing on the real plane wing it was discovered the arc angle had to be reduced to 23.75 °. This angle was calculated by purely hit and trial method. After determining the correct angle for the arm another issue was that since UR5 is a collaborative robot, the protective stops on it are extremely sensitive, forcing the robots to stop midway. To counter that the force limit on the UR teach pendant was increased to 250N each.

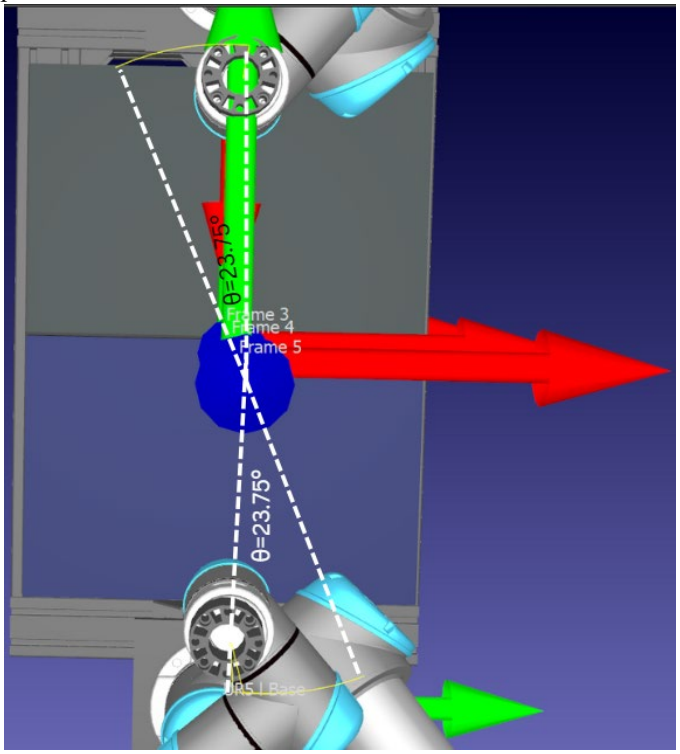

Fig. 6. Circular motion of the robots for turning the nozzle.

In summary, the testing and demonstration phase confirmed that the dual-arm robotic system, once precisely synchronised with mirrored poses and matched speed profiles was able to mimic the human-like motions to attach and detach a fuel nozzle to a plane wing.

IV. Conclusion and Future Work

This study presents a novel dual-arm commercial aircraft ground refuelling robot system demonstrator. A TRL4 system demonstrator is developed using two collaborative robots integrated on a mobile platform with the robots' tool flanges connected using a shared tool interface that holds a standardised aviation fuel nozzle. The system concept was initially validated in a RoboDK simulation followed by real-world test using an Airbus A320 wing (fuel tank) and fuel port. It was demonstrated that the system can reliably and repeatably insert the nozzle to the fuel port, lock, unlock, and remove over more than 20 cycles.

In the next phase of the research, sensor package including machine vision system and force-torque sensing will be integrated to the robot system. For further future work, the synchronization will be improved as the current method is temporal and not kinematic where both arms begin movements at nearly the same time, but there is no dependency between the two arms or real-time position correction. Improved co-dependency would require intertwined motion planning with shared Jacobians, centralised planners, and impedance control to handle dynamic interaction.

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