BB Segment Grasping Pipeline with Variable Admittance Control for EU DEMO Remote Maintenance

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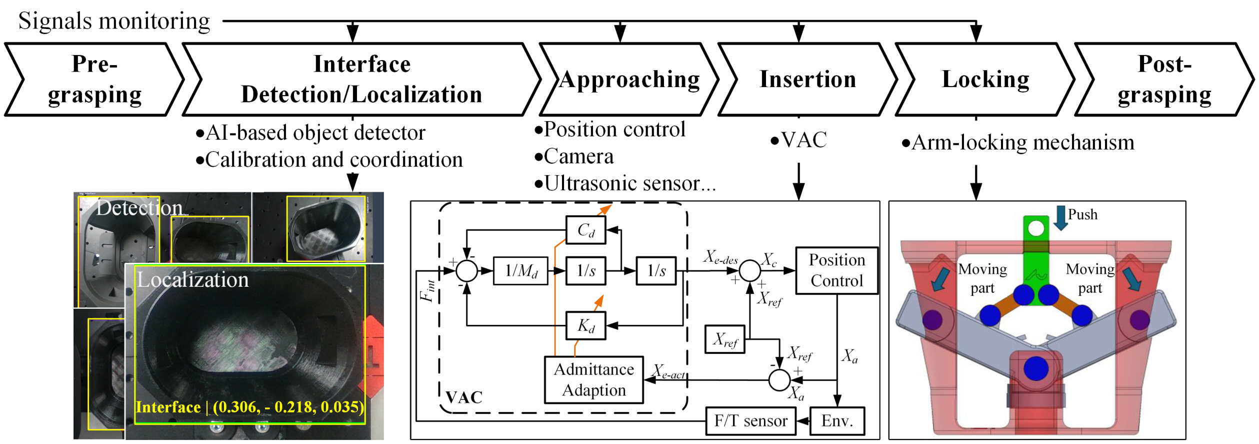

Fig. 1: Pipeline of grasping process for breeding blanket segments removal

***Index Terms*—EU DEMO, Maintenance and Remote Handling, BB Segment Grasping, Admittance Control**

Summary

Secure grasping of the EU DEMO breeding blanket (BB) segments is needed to achieve reliable remote handling for replacement through the upper port. The grasping pipeline is broken into four tasks: interface detection and localization, approach, insertion and locking. Solutions are proposed and tested for each step using down-scaled prototypes of the gripper and interface, off-the-shelf sensors and actuators and a UR3e manipulator. An admittance control scheme with variable admittance parameters is implemented to robustly solve the challenging insertion step, in which high accuracy and safety must be maintained while some degree of collision between the gripper and BB segment is practically unavoidable. The admittance controller allows the grasping procedure to recover if the approach fails within a certain tolerance, and allows the geometry of the interface to guide the gripper into the correct position for locking. The code for this project is available on GitHub.[1]

I. Background and Motivation

A robust remote maintenance architecture will be necessary for the safe and economical functioning of the EU DEMO power plant. The removal and replacement of BB segments through the upper port requires a folding gripper which locks into a countersunk interface hole in each BB segment's exposed area in the upper port [1]. The folding gripper's arms and conical contact surfaces passively transfer the weight of the BB segment to the robotic RH tool, including large moments due to the distant center of mass of the segment, enabling the BB segment to be transported. A stable grasp requires the gripper to fit tightly in the interface, therefore an accurate and precise insertion is required while maintaining safety. A comprehensive and robust grasping pipeline must be laid out which can meet these requirements. Each step should be clearly defined, scalable and task-oriented, enabling parallel testing of solutions using down-scaled prototypes with generic manipulators which can later be integrated and scaled up. Fig. 1 details the identified grasping pipeline steps along with solutions proposed and tested in this work.

Due to having the highest probability of collision (which could cause large forces due to the high stiffness of the stainless steel constructions of the gripper and BB segment), the insertion step is considered to be the most critical. The conical faces of the gripper and interface can guide the gripper into a successful insertion if the gripper is allowed to deviate from its planned trajectory. Impedance and admittance control are related schemes, often implemented in collaborative robots (cobots), which allow the system to behave compliantly (as a mass-spring-damper) in response to external forces [2]. An admittance controller with variable admittance parameters is proposed and tested for the gripper insertion in this work.

II. Grasping Pipeline

The grasping pipeline (Fig. 1) begins with the detection and localization of the interface. This is necessary to overcome uncertainties in the positions of the interface and the gripper. A stereo camera sensor mounted on the gripper is proposed

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[1] https://github.com/XingyuYangAU/IAFA_FEC2025_AU_robotics

to solve this step. Together with an AI-based (YOLOv8n) object detector and hand-eye calibration, the interface position relative to the gripper can be determined. Next, the gripper must approach the interface based on the localization and depth data. At close range, the object detection and stereo depth data becomes unreliable and an alternative should be used, thus an ultrasonic depth sensor is proposed.

The insertion step is commenced at a threshold distance x_t, shortly before the gripper would make contact with the upper surface of the BB segment. For robust and accurate insertion, an admittance controller is proposed, which allows the manipulator to respond to collisions by adjusting the gripper trajectory. Within Fig. 1, the block diagram of the tested variable admittance controller (VAC) is shown. The virtual stiffness and damping matrices are scaled by factors of the form $s = 1 + (s_m - 1)(1 - x/x_t)$, where x is the distance from the final position and s_m is a maximum scale factor. This gives smaller deflections in response to contact forces as the gripper is inserted further into the interface.

Once the final position is reached, the folding mechanism is engaged, locking the gripper inside the interface. Successful engagement of the mechanism is sensed using a proposed force sensor at the end of each folding arm.

III. Results and Discussion

Fig. 2 shows the experimental setup, including the actuated 3D-printed gripper prototype with folding locking mechanism, matching BB segment interface, proposed stereo camera, ultrasonic depth sensor and folding arm force sensors. The gripper is mounted on a UR3e cobot manipulator since a down-scaled RH tool is not available yet. The built-in force-torque sensor of the outermost link is used to implement the VAC scheme.

Data from a successful insertion test using VAC is displayed in Fig 3. In part (b) of the trajectory, the gripper collides with the upper surface of the blanket due to a failed approach in part (a), resulting in large vertical forces and a rebound of the gripper visible in the force and displacement data. The VAC then automatically continues along an altered trajectory in part (c), initiating a partial insertion in which the conical gripper and interface surfaces slide against each other. The resulting $x-$ and $y-$ contact forces are visible in the data. In part (d), the gripper has successfully reached the end position at the bottom of the interface.

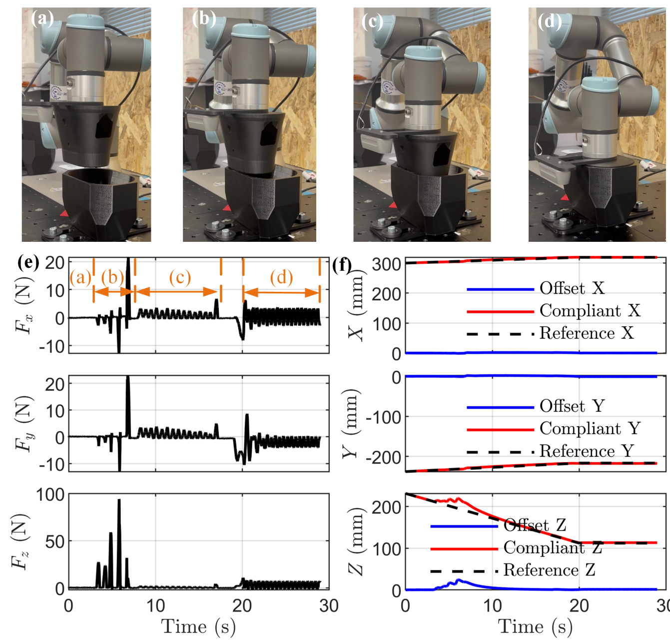

Fig. 3: VAC for gripper insertion: (a) Initial pose, (b) Colliding with upper surface, (c) Sliding in, (d) Insertion done, (e) Interaction force in three directions, and (e) Motion response in three directions

This test demonstrates the robustness and safety characteristics of the VAC in its ability to recover from collisions resulting from a failed approach trajectory, as well as the ability to successfully take advantage of the conical gripper and interface to slide the gripper to the correct end position. On the other hand, the admittance control scheme causes small oscillations of the gripper when fully inserted as seen in part (d) of the force data; these would be avoided by switching to impedance control on a different manipulator allowing for direct force control of the joints. The impedance parameters could also be optimized using reinforcement learning.

Work is ongoing to integrate and improve the proposed grasping pipeline. Localization of the interface depth can be improved by using the integrated active infrared sensor of the camera. The grasping pipeline can also be integrated into the overall BB segment manipulation task with a down-scaled RH tool. Temperature and radiation conditions in the vacuum vessel should be taken into account in the selection and placement of sensors, and more realistic results can be obtained by testing with accurate materials and larger scales.

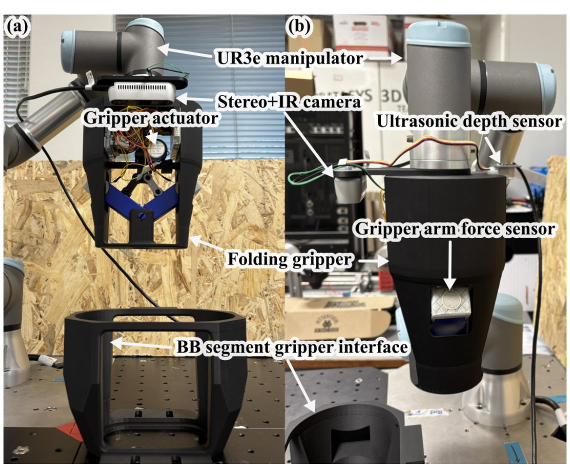

Fig. 2: Experimental setup: (a) front view, (b) side view

References

[1] T. Steinbacher, C. Bachmann, C. Gliss, G. Janeschitz, and R. Mozzillo, “Design of the gripper interlock that engages with the DEMO breeding blanket during remote maintenance,” *Fusion Engineering and Design*, vol. 193, p. 113641, Aug. 2023.

[2] A. Q. Keemink, H. van der Kooij, and A. H. Stienen, “Admittance control for physical human–robot interaction,” *The International Journal of Robotics Research*, vol. 37, pp. 1421–1444, Sept. 2018.