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Advanced 6-Dof Mobile Manipulator for Assembly Tasks

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Abstract:- The main difference between autonomous robotic assembly and the conventional hard automation that is used in large-scale production today is how components are located, obtained, manipulated, aligned, and assembled. It is possible for an autonomous robotic assembly system to manage inherent uncertainties, unknowns, and extraordinary scenarios because of its great flexibility and adaptability. The purpose of this study is to present an autonomous mobile manipulator that can efficiently handle these exceptions and uncertainty. It accomplishes this by utilizing sophisticated reactive task management, coordinated control, and a mix of force- and vision-based guiding. The mobile manipulation system has demonstrated via experiments that it is extremely dependable while carrying out jobs like "Pick and Place" type insertion assembly, which is frequently encountered in the assembly of automobile and other industries.

I. INTRODUCTION

In various fields, there is a growing demand for robots that can perform intricate and skillful manipulation tasks. A notable example is the requirement for automated assembly, spanning from terrestrial applications like factory assembly lines to extraterrestrial scenarios such as assembling lunar habitats. Robotic manipulation is becoming increasingly integral to these tasks. While current robotic systems excel in many tasks, especially in structured factory environments, they are typically tailored for specific, relatively simple tasks that can be accomplished with basic technology. Often, both hardware and software are designed with a narrow focus. Looking ahead, future robots will need to take on a wide range of responsibilities, from transporting payloads across expansive workspaces to precisely inserting or placing small components. These tasks will be highly diverse and complex. Mobile manipulators, equipped with both dexterity and mobility, are well-suited to tackle these intricate assembly tasks.

Although mobile manipulators possess the mobility and dexterity required for assembly tasks, the crucial role of sensors and software cannot be overstated in achieving successful outcomes. Regardless of the complexity of the scenario, a mobile manipulator must have the ability to perceive its surroundings, make decisions based on environmental conditions, and execute actions informed by those decisions.

In this paper, we present our work on an advanced mobile manipulator designed for assembly tasks within the realm of automotive manufacturing. First, we discuss our controller, which coordinates the movements of both the mobile base and manipulator to achieve desired end-effector positions while maintaining high manipulability. Next, we introduce different control approaches that incorporate combinations of visual servoing and force control, comparing their effectiveness in performing precise "peg-in-hole" insertion assembly tasks. We establish a framework for constraining the manipulator's end-effector based on position and/or force using a high-frequency, low-level controller, and integrate this with a sophisticated task-level executive. Finally, we demonstrate the system's capabilities through repeated experiments involving the insertion task on an automotive task board. The results underscore our ability to successfully accomplish these precision assembly tasks with high reliability and resilience to errors, even when the robot starts from varying and unknown positions.

II. OVERVIEW OF APPROACH AND RELATED WORK

Our research objective is to autonomously execute intricate assembly tasks with a high level of sophistication. To accomplish this goal, we've developed an autonomous mobile manipulator that excels in overcoming inherent uncertainties and exceptional situations within the system. This achievement is marked by remarkable performance and reliability, made possible by employing control strategies that encompass coordinated control of both the mobile base and manipulator. Additionally, we combine visual and force-based guidance methods, and we incorporate advanced reactive task-level control.

Coordinating the movements of the mobile base and manipulator extends the manipulator's operational range. The synergy between visual and force-based guidance not only enhances system performance but also surpasses what either method could achieve in isolation. Task-level control provides a framework for adaptable and dependable task execution. In the subsequent sections, we delve into these three key elements of our approach, which together enable high-performance and dependable mobile manipulation.

A. Coordinated Control of Base and Manipulator

Mobile manipulators offer significant advantages in manufacturing assembly applications, particularly in terms of task flexibility and robotic mobility. In contrast to traditional industrial robots, mobile manipulators excel in their ability to adapt to changing environments and perform a wide range of assembly tasks. By equipping these manipulators with mobility platforms, they can seamlessly transition between work areas, parts feeders, and even moving assembly lines.

Early research in mobile manipulation initially treated the mobile base and the manipulator as separate components. This approach had its limitations, as highlighted by Shin et al., emphasizing the need for better coordination. They introduced a system that employed the decoupled motion of the mobile manipulator, where the base remained stationary while the manipulator moved. While this approach ensured precise tracking of the end effector, it extended task completion times due to the need for occasional pauses to reposition the base. Their planning strategy optimized base positions to enhance the manipulator's maneuverability along the desired trajectory while minimizing the number of base repositions.

In the context of coordinating mobile bases and manipulators, various authors have contributed to the literature, primarily focusing on dynamics, such as controlling forces and torques, rather than positions and velocities, which differs from our kinematic approach. Some authors explored internal control strategies within this dynamic context. For instance, Yamamoto and Yun described a dynamic coordinated controller that constrained the end effector to follow a trajectory while controlling the base to maintain arm maneuverability whenever possible. Similarly, Holmberg and Khatib developed a dynamically decoupled control model to achieve smooth and precise control of a mobile base, minimizing forces on it while ensuring coordinated motion. Kim et al. presented a coordinated control scheme utilizing the null space of an overactuated mobile manipulator to achieve dynamically stable motion.

B. Combining Visual and Force Servoing

In robotic assembly, one of the most important control jobs is the physical connecting of components. Here, we combine visual servoing with force servoing to improve system resilience without requiring fine-grained global reference coordinates or extremely perfect visual sensing. First, visual servoing is used to roughly align the end-effector of the mobile manipulator within the assembly region. Next, a combined pose and force hybrid control strategy (described in Section 5) allows the mobile manipulator to overcome the geometric uncertainty caused by visual servoing. This enables it to come into touch with the task board and carry out the peg-in-hole assembly with tight tolerances and exact placement control.

Early work on pose/force control, as pioneered by Mason (1979), focused on defining constraint frames based on both natural and artificial constraints. This approach aimed to ensure that the robot's movements were limited within specific boundaries to achieve desired poses and forces.

Building upon this foundation, Raibert and Craig (1981) introduced a hybrid pose/force control scheme that utilized separate pose and force controllers. This separation helped to avoid conflicts that could arise between force and pose constraints, allowing for more efficient and effective control of the robot's movements.

Yoshikawa (1987) further expanded on this concept by incorporating manipulator dynamics into the control scheme. By considering the dynamic behavior of the robot, Yoshikawa demonstrated that accurate dynamic models could be used to achieve desired poses and forces. This insight opened up new possibilities for achieving precise control in robotic systems.

In more recent work, force feedback and control have been extensively utilized in service and industrial robotics. These applications involve tasks such as object locating, tracking, picking up, carrying, and placing in human-friendly environments. The precision requirements for these tasks can vary, with industrial robots typically requiring higher levels of precision due to the demands of industrial applications. Force feedback is also employed for precise object sensing when other sensors may not provide sufficient accuracy. By using force feedback, robots can gather information about the forces exerted on objects, allowing for more precise manipulation and interaction with the environment. Overall, the development of pose/force control techniques has greatly advanced the capabilities of robotic systems, enabling them to perform complex tasks with high levels of precision and adaptability.

III. APPLICATION AND EXPERIMENTAL SYSTEM

This section details the application scenario that we are tack- ling and the mobile manipulator that we designed, which was used for the experiments.

In today's automotive industry, robots are a common sight on body assembly lines, yet there remain various tasks within general automotive assembly that still rely on human labor. This project focuses on a different example of such a manual task, which involves the precise "picking and placing" of electronic components. In this case, the task entails carefully selecting electronic components from a designated location and accurately placing them in their respective positions. For our experimental purposes, we've obtained a specialized setup designed for this task, which we'll refer to as the task board (Fig. 2). The objective of this scenario is to adeptly pick electronic components and place them precisely in their designated locations on the task board, starting from an initial position near the board. To aid in visual identification and servoing, a camera marker is mounted on the task board. This task demands precise positioning, with tolerances as tight as a few millimeters..

- *The Mobile Manipulator*

To achieve this task, we developed an advanced mobile manipulator. The mobile manipulator, shown in Fig. 1

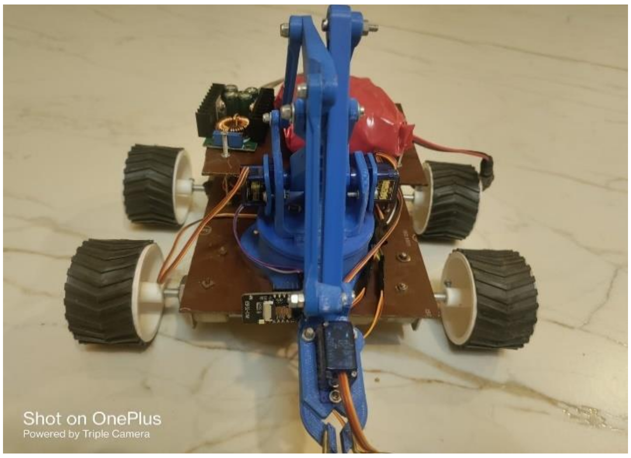

Fig 1 The Mobile Manipulator is Made Up of a 6-DOF Arm on a Power Bot Base.

The manipulator is a 6-DOF 3d printed arm. Controlled by an ESP8266 controller, this agile system seamlessly integrates with an ESP32 camera, enabling real-time vision feedback. The 3D-printed arm combines lightweight design with precision, allowing it to handle various objects with ease. The mobile platform enhances flexibility, enabling the robot to navigate and execute tasks across diverse environments. This synergy of innovative hardware and advanced control systems ensures efficient and accurate pick-and-place operations, making it a valuable asset for automation and logistics in constrained spaces.

IV. COORDINATED CONTROL

This section highlights our work on coordination of a dexter- ous manipulator and mobile base to achieve flexible 6-DOF end effector placement.

- *Resolved Motion Rate Control (RMRC)*

Historically, Resolved Motion Rate Control (RMRC) has been used to control manipulators with a high degree of freedom. Reactive algorithms like RMRC have the benefit of not requiring inverse kinematics techniques, which can lead to a lot of numerical issues like non-unique solutions. In contrast, RMRC uses the Jacobian matrix to translate joint velocities to end effector velocities.

$$\upsilon = \boldsymbol{J}(q)\dot{q}, \qquad (1)$$

Where J is the Jacobian and q and υ stand for the state and velocity of the controllable degrees of freedom. It is evident from rear-ranging that the inverse Jacobian—or, in the absence of the inverse, the pseudo-inverse—is used to translate desired end effector velocities into joint velocities.

Mobile manipulators may also be controlled with this control technique. By this extension, the base and arm Jacobians are combined to form the Jacobian.

$$\upsilon = [JBase(q)JArm(q)]\dot{q}. \qquad (2)$$

As with the manipulator Jacobian, motions of the mobile base map to linear and angular velocities of the end effec- tor via the mobile base Jacobian. That mapping is depen- dent on the configuration of the manipulator, meaning that motions of the mobile base will affect the end effector lin- ear and angular velocities differently given the manipulator joint angles. The mobile base Jacobian is also dependent onthe particular base and its mode of control.

V. INTEGRATING FORCE AND VISION SERVOING

Many researchers employ a servo-ing approach to "peg-in-hole" type insertions because of sensor uncertainty. We are attempting to place a plug in a target hole (Fig. 2) in our application, where the tolerance is comparable to the noise from the sensor. This makes insertion particularly difficult to be reliable. We use a combination of force servoing and visual techniques to overcome this. Both servo techniques and their various combinations are covered in this section. The effectiveness and efficiency of the various approaches are demonstrated by the results that are given.

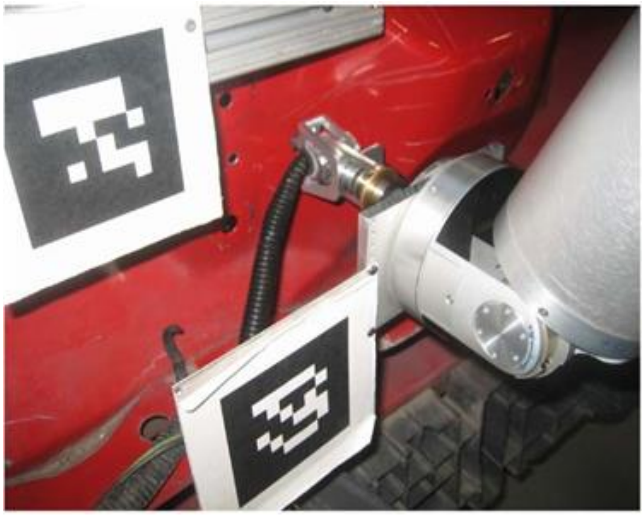

Fig 2 The Plug is Moved Toward the Target by the Arm.

A. *Visual Servoing*

Every command is transmitted with reference to the end-effector's present location. The controller modifies the desired position of the end-effector in the following ways if pm is the measured relative position from the cameras and pd is the desired position of the end-effector with respect to the target body:

$$perr,t = pd - pm,$$

$$pcmd = kpperr,t + kd\,(perr,t - perr,t - 1) + ki \int perr \qquad (10)$$

Where pcmd represents the end-effector's commanded position in relation to its current position. The command is given by the controlling process along with the PID gains to be utilized. After converting the relative position command into a new desired position in the global reference frame, the controller integrates the new position to get the required velocity. Lastly, the velocity control law from the preceding section is put into practice.

B. Force Servoing

We implemented a basic force controller that enables the end-effector to establish and sustain appropriate contact forces with the objects it meets by using force feedback data from the manipulator.

The way our force controller functions is by using force feedback to change the end-effector's location. The controller pushes the end-effector in that direction if the required contract force error is too small in that dimension (in the end-effector frame). The controller pushes the end-effector in the opposite direction if the force error is too large.

C. Servoing Strategies

Position control on the end effector is handled by the coordinated controller and is dependent on arm and mobile base pose updates. Although base position updates are received at a rate above 10 Hz, this frequency is insufficient to perform activities with millimeter accuracy. Lastly, all of the moves that result in motions stopping in the event of unexpected forces are combined with force limitations.

After trying to reach the last waypoint, the arm is moved rearward to confirm that the insertion was successful. The plug has been successfully fitted, according to the system, if a significant force is sensed (see to Appendix A). If not, the system tries the insertion a predetermined number of times before giving up and alerting the user if the insertions keep failing..

In the second approach, force insertion, visual servo is only used as a preliminary alignment stage. A sequence of restricted motion instructions with force limits and force control are then used to complete the insertion. The end effector must make contact with the surface in order to begin the force insertion task. This is a quite straightforward issue: Once the visual servo alignment is complete and the plug is roughly perpendicular to the surface, the system directs the end effector to advance until it detects a significant force in the negative Z direction. This force indicates that the plug is pressing against the surface, most likely. A list of all the force limitations, thresholds, and gains utilized in the force insertion can be found in Appendix A.

After locating the surface, the system's next task is to locate the target hole. This is achieved using a spiral motion technique. Assuming the plug is oriented roughly perpendicular to the surface, a specific motion command is executed to make the end effector spiral outward from the point where it made contact with the surface. This spiral motion is controlled in the X (down) - Y (right) plane of the end effector. To ensure that the plug maintains contact with the surface, a regulator constraint is applied using force control in the Z direction of the end effector. When the plug crosses the target hole, the force in the Z direction decreases as it is no longer pressing against the surface. At this point, the force controller pushes the plug slightly into the hole. Once the plug is securely inside the hole, the spiral motion ceases. To ensure safety, a hard limit constraint is in place to halt motion when a significant force is detected in the plane of the spiral (the X and Y directions).

Once the target hole is identified, the system initiates a constrained motion command, moving the end effector forward until a very high force reading is registered, indicating that the plug is fully inserted. Subsequently, the end effector is directed to pull away from the surface. The same verification check as in the visual servo approach is employed to confirm the successful plug insertion. Figure 8 illustrates the forces acting on the end effector during the insertion process.

The third approach integrates both visual servo and force insertion (abbreviated as VS-FI). It begins with a visual servo, aligning the system to the same approximate waypoint as in the previous two schemes. Then, an attempt is made to perform a visual servo, following the same force limitations on the end effector as in the first scheme. After the visual servo concludes, the system proceeds with the force insertion technique. This scheme also utilizes the autonomous plug-docked check. The underlying idea here is that the visual servo might succeed independently, potentially obviating the need for force insertion.

The combination of visual servoing followed by force insertion proves to be the most successful approach, with only six failed attempts and no trial failures. While the visual servo alone lacks the precision to reliably insert the plug into the target hole, force insertion compensates quickly for minor alignment errors. This approach demonstrated effectiveness even when the plug was misaligned from the target hole by up to 20 mm. The unsuccessful attempts for this scheme primarily resulted from poor initial alignments in the visual servo, with the waypoint being at a significant distance from the surface.

There are alternative methods to integrate visual and force feedback. For instance, a control scheme could simultaneously utilize visual information for left/right and up/down adjustments concerning the target hole, while using force feedback to maintain contact with the task board and facilitate plug insertion. Exploring these alternative combinations is a potential avenue for future research.

VI. RESULTS

A. Reliability Tests

To evaluate the system's reliability, an extensive battery of tests was conducted, encompassing over 100 experiments wherein the mobile manipulator executed the task described in the preceding section. The mobile manipulator, as well as the task board utilized, conforms to the specifications detailed in Section 3 and is visually represented in Figures.

In these experiments, the robot was instructed to locate the task board, approach it, and successfully insert the plug. The tests encompassed a systematic exploration of starting locations and angles, with the robot commencing its task from a meticulously sampled grid. This grid was discretized to include testing locations spaced at 0.5-meter intervals, effectively covering the area spanning from 1.5 to 2.5 meters longitudinally from the task board and from 2 to 2 meters laterally. Locations positioned over 3 meters away from the task board were excluded from consideration, owing to the inherent unreliability of visual pose estimation at such distances, as elaborated in Section 5.

At each location within the grid, the mobile manipulator was initiated at five different angles, specifically 60, 30, 0, -30, and -60 degrees. It's noteworthy that due to the robot's configuration, which places the camera to one side of the manipulator arm, the task board's ARTag fiducial marker was not visible from all starting angles. Consequently, these non-visible locations were not included in the analysis. A visual representation of the testing locations employed can be found.

B. *Analysis*

The extensive reliability tests yielded valuable insights into the system's performance and robustness. These experiments aimed to assess the system's ability to consistently complete the designated task under diverse conditions.

The key findings from the reliability tests are as follows:

- **Coverage and Robustness:** The grid-based approach, spanning a wide range of starting locations and angles, enabled the system to demonstrate a comprehensive coverage of the workspace around the task board. This indicates the system's adaptability and robustness in handling different spatial configurations.
- **Exclusion of Unreliable Angles:** The exclusion of testing locations where the ARTag fiducial marker was not visible from certain angles is a pragmatic approach, acknowledging the system's limitations in those scenarios and avoiding unreliable data.
- **Reliability Assessment:** The repetition of experiments, totaling over 100 runs, allowed for a reliable evaluation of the system's consistency in completing the task. The high number of experiments provides statistical confidence in the reported results.

Overall, the reliability tests serve as a foundational assessment of the system's capabilities, highlighting its adaptability to various spatial scenarios and the importance of avoiding unreliable data in the evaluation process. These findings lay the groundwork for further refinement and improvement of the system's performance in real-world applications.

VII. CONCLUSIONS

The realm of robotic assembly demands a system endowed with exceptional flexibility, adept at navigating the intricacies of inherent uncertainties and exceptions. An emergent and promising solution to address these challenges lies in the development of a resilient mobile manipulation system. This paper presents an autonomous mobile manipulator equipped with the potential to adeptly overcome uncertainties and exceptions, achieved through the integration of three pivotal technologies: coordinated base and manipulator control, the fusion of visual and force servoing, and the incorporation of error recovery via adaptable task-level control.

Specifically, the inclusion of constrained motion primitives capable of detecting constraint violation conditions empowers the system with reactive task control, significantly amplifying overall robustness. Through rigorous experimental demonstrations, this mobile manipulation system exhibits remarkable system robustness and reliability, particularly in the context of a "peg-in-a-hole" task commonly encountered within automotive wiring harness assembly.

The pursuit of a robust, reliable, and capable autonomous robotic assembly system, if successfully realized, has the potential to usher in a paradigm shift in the approach to robotic assembly. This transformation promises a more responsive, adaptable, and intelligent system, thereby diminishing the need for extensive human intervention and liberating manufacturing and assembly environments from the constraints of precise and rigid structural requirements. The culmination of these advancements holds the potential to revolutionize the landscape of automated assembly, shaping a future where efficiency and adaptability coalesce seamlessly.

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APPENDIX A: GAINS AND THRESHOLDS USED IN THE DOCKING EXPERIMENTS

Gain/Threshold	Value	Dimension	Method of Determining
Visual Servo Proportional Gain	0.7	XYZ relative to waypoint	Trial and error to maximize success and time of completion
Visual Servo Waypoint Distance Tolerance	3 cm total (XYZ)	XYZ relative to waypoint	Trial and error to maximize success and time of completion
Visual Servo Waypoint Angular Tolerance	5 degrees in each direction	Roll, Pitch, Yaw relative to waypoint	Trial and error to maximize success and time of completion
Touch Board Force Threshold	-12 Newtons	Z relative to gripper	Analyzed data of experiments driving gripper towards task board
Maintain Contact with Board Force Target	-14 Newtons	Z relative to gripper	Trial and error to maintain contact with task board
Maintain Contact with Board Proportional Gain	0.0015 meters/Newtons	Z relative to gripper	Trial and error to maintain contact
Find Hole Force Threshold	+20 Newtons	XY relative to gripper	Data analysis of experiments sliding plug along task board freely vs. catching target hole
Stop Inserting Plug Force Threshold	-40 Newtons	Z relative to gripper	Data analysis of experiments pushing