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Force control heuristics for surpassing pose uncertainty in mobile robotic assembly platforms

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***Abstract*—This paper presents a collaborative mobile manipulator assembly station, which uses force control to surpass the positional uncertainties arising from unstructured work environments and positional errors of the mobile platform. For this purpose, the use case of an internal combustion engine for the automotive industry was considered. Several force control heuristics relying on blind searches using oscillations and/or environment exploration were developed and implemented. Particular attention was given to the orientation errors of the mobile platform, as it was proved that they have a significant impact on the assembly task. The proposed heuristics showed great potential for the use case at hand. Particularly, when the orientation error of the platform is limited to $\pm 2°$, the oscillation method complemented by environment exploration was able to surpass a maximum translation error of $32.3\mathrm{mm}$, whereas the environment exploration complemented by orientation correction was able to surpass an error of $73.3\mathrm{mm}$. Moreover, a generalization strategy was proposed, intending to expand the scope of the developed heuristics to other assembly applications.**

***Index Terms*—Compliant robotic assembly, Mobile manipulator, Force control**

I. Introduction

Since its announcement, the Industry 4.0 initiative correlates technological innovation with the growing need to offer highly customized services and products, low production volume per manufacturing order, and the decrease in the lifetime of products and production systems. Productive entities are also increasingly expected to see substantial improvements in the quality and reliability of their products, taking into account responsible management of costs and environmental impacts. Likewise, demographic changes in Western society poses additional challenges, particularly in Europe, where there is a widespread ageing of the working population. The empowerment of employees assigned to productive tasks is thus becoming increasingly important, with a view for achieving intelligent distribution of the available workforce.

The recent technological innovations in the area of robotics and cyber-physical systems not only allow workers to focus on tasks with greater added value, freeing them from less ergonomic and less valuable tasks, but also provide companies with innovative tools to facilitate production operations in a collaborative context. Despite these technology innovations, today's modern industries still heavily rely on manual assembly processes [1], [2], with its typical shortcomings of inconsistency and low efficiency. Furthermore, manual assembly of heavy components may cause repetitive stress injuries to the workers [3]. This reality can be explained essentially due to the high dependence of robotic assembly's on their positional precision relative to its working environment. The implementation of dedicated large-scale robotic assembly stations with highly structured work environments is capable of solving these problems but can only be employed in mass production industries due to their large inherent costs. Discrete production, or production of small batch sizes, usually relies on unstructured work environments, which leads to higher position and orientation uncertainties. Furthermore, due to the aforementioned uncertainties, a robot control strategy based solely on position control can be ineffective and insufficient for the successful implementation of an assembly task [4], [5].

Several different approaches may be employed to achieve flexible robotized assembly solutions for unstructured work environments. Event-based search strategies using force control, vision-based strategies, or hybrid strategies (employing computer vision to estimate the position of the station and force control to complete the assembly) are among the most usual approaches [1]. Typically, vision-based strategies can overcome larger uncertainties, tremendously increasing process flexibility. However, this strategy is highly reliant on ambient light conditions and camera calibration processes, which may be troublesome and is often responsible for the failure of this method [5]. On the other hand, force-based strategies do not exhibit the enumerated shortcomings but tend to be more limited regarding the range of uncertainties that can be overcome.

Bearing these ideas in mind, this paper addresses the development of a mobile manipulator, with built-in force sensors for executing assembly tasks in an automotive production line scenario. The implementation of such agile collaborative robotic solutions will provide companies with the proper tools to increase the automation level of this kind of operations, while conserving the agility to dynamically adapt the robotic solution to other production line requirements, with shorter setup-times, inline with the market changes. To deliver such a solution, additional challenges need to be overcome, such as the imprecision in the positioning of the mobile platform and positional uncertainties of the unstructured assembly station.

The remainder of the paper is organized as follows: after this introductory section, Section II presents a short review of the state-of-art on force control algorithms for robotic assembly applications. Section III describes the automotive use

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case scenario. Section IV presents the adopted force control strategy. Section V and VI present the results and propose a generalization concept for the developed control strategy, respectively. Finally, in Section VII the main conclusions will be addressed.

II. State of the Art

Force control algorithms increased the scope of robotics as they provided the essential tools for a robotic system to be able to apply a specific force or to react to an external force in a predetermined manner. These algorithms can be implemented actively or passively, depending on whether the force and torque measurements are fed back into the controller.

Passive force control is an open loop control algorithm without feedback of force information and, therefore, its force output is constant (cannot react to external stimuli). The implementation of passive force control is usually accomplished at tool level and can be used to accomplish simple assembly tasks with small position uncertainties and considerable assembly tolerances. Passive force control tools can be materialized by numerous technological solutions, such as spring-controlled systems, mass counterbalanced systems and pneumatic actuators [1].

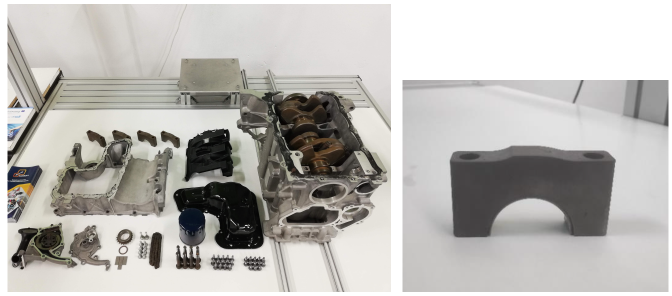
Active force control is a closed loop control algorithm with feedback of force measurement. These algorithms implement a reactive control strategy that is accomplished at the controller level and allow the system to achieve a compliant behavior. The implementation of active force control is usually more costly than passive solutions, but also tends to result in a more robust system, with better accuracy and repeatability [6], [7].

Hybrid force/position control, impedance control and admittance control are some of the most common active force control algorithms [1]. From these, the most relevant for the scope of compliant assembly tasks is the impedance control mode (in which the system's positional error is used to tune its force response [8]), as it is the most stable method for collision control [7], [9].

Moreover, active and passive force control methods are not mutually exclusive, meaning that they can be used simultaneously to achieve better cycle times and ability to adapt to external stimuli [1].

III. Automotive Use Case Description

Automotive companies face a high variability of models with a high production throughput and significant volume variation along their life-cycle. Their manufacturing systems tend to be over-automatized, leading to high investments in resources and lack of flexibility. Automotive manufacturers do not need to automatize more, but need a dynamically re-configurable production system, enabling an incremental amortization of workstations and supporting human operators with the execution of production tasks. In this context, a laboratory setup was established, where a mobile manipulator was designed to operate as a mobile assembly station, with the capability of moving between workstations (engine assembly stations), transporting assembly parts between them, and performing the required assembly tasks.



(a) Engine assembly workstation (b) Bearing cap

Fig. 1. Automotive industry use case scenario.

Figure 1a presents the collaborative workstation where the engine is assembled. Here, the mobile manipulator is responsible for the insertion of a bearing cap (depicted in Figure 1b) on a main bearing journal of a crankshaft. This assembly step was chosen because it is isolated enough so that big uncertainty values can be tested without interference of other components, thus removing elements that could influence the results of the proposed approach.

A. Mobile Manipulator Description

The developed mobile manipulator (depicted in Figure 2) is composed of a collaborative robotic manipulator (Kuka LBR iiwa 14) mounted on top of a mobile platform developed by Sarkkis Robotics.

The robotic arm is equipped with a joint-torque sensor in each axis, allowing it to achieve a compliant behavior by estimation of the applied external forces (albeit not as accurately as a dedicated external force/torque sensor). Its traits of dexterity, kinematic redundancy and inherent compliance are particularly compelling for assembly tasks as they allow insertion, screwing and handling of delicate parts [10].

Fig. 2. Mobile manipulator developed for assembly operations.

Regarding the mobile platform, it is equipped with two safety laser scanners (Sick S300 Expert), used not only for purposes of self-localization and navigation but also to guarantee that all safety standards are met. As far as the robot's traction system is concerned, the choice fell on a differential solution, as it allows a smoother movement in confined spaces, creating less instability and consequently greater precision in the manipulator movements.

Finally, an adaptive gripper was utilized, Robotiq's 2F-85, which is particularly suited for usage with collaborative robots, as it can control its exerted gripping force.

B. Software Architecture

The mobile manipulator's software architecture, depicted in Figure 3, was built on top of the ROS (Robot Operating System) framework, relying on topics, services and actions to exchange information between different subsystems.

The orchestration of the tasks between the mobile platform and the Kuka arm is established using a software package named Task Manager (TM), introduced by authors in [11]. Here, each robot task has a corresponding software skill, that is controlled by the TM. Please refer to Figure 3.

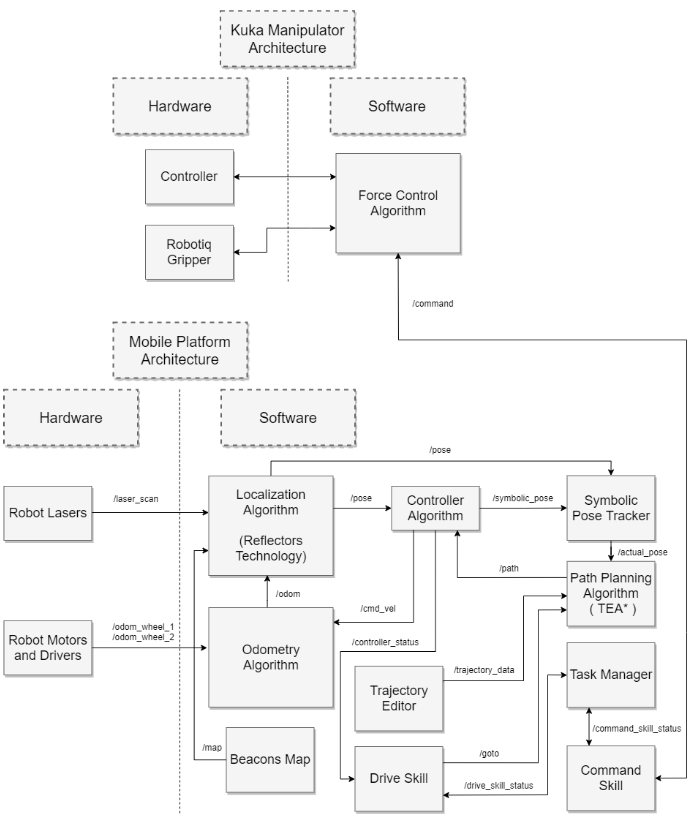


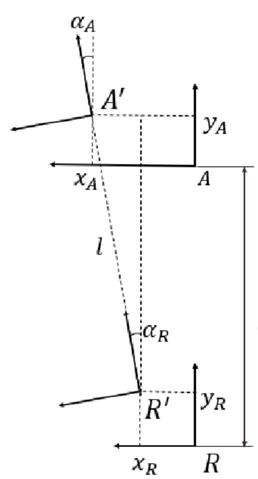
Fig. 3. Mobile Platform Software Architecture.

The mobile platform's navigation system is composed of several software modules, namely: motion controller, robot self-localization, trajectory generation, and robot fleet management and coordination.

Regarding the used force control algorithms, the selected collaborative manipulator is equipped with several different control modes. For the scope of the mobile assembly station, apart from the traditional positional controller, two main control modes were explored - the Cartesian Impedance Controller and the Cartesian Impedance Controller with overlaid force oscillation. Both these types of controller are based on the principals of the aforementioned impedance control mode. However, the former corresponds to its simple implementation, while the latter allows for forces/torques to be overlaid on one degree of freedom, causing the system to deviate from its programmed path in a controlled manner.

C. Mobile Manipulator's Impact on the Assembly Operation

Flexible production systems often rely on unstructured work environments with inherent uncertainties regarding the position and orientation of its components. The introduction of a mobile manipulator is a further source of positional uncertainties, as its positioning system usually cannot guarantee an accuracy smaller than the assembly tolerance. As such it is crucial to consider how the positional errors of the mobile manipulator will impact the assembly operation. Figure 4 represents a schematic view of the impact of positional errors of the mobile platform (as seen from above). The reference frames R and A correspond to the programmed reference frames for the mobile platform and assembly (ideal scenario - without any positional errors), respectively. In turn, R' corresponds to the approach position of the mobile platform with a certain error relative to R (real scenario). Finally, A' corresponds to the perceived assembly position, when the mobile platform is positioned in R'.



$$\begin{cases} x_A = x_R - l \cdot \sin \alpha_A \\ y_A = y_R - l \cdot (1 - \cos \alpha_A) \\ \alpha_A = \alpha_R \end{cases}$$

Fig. 4. Impact of the mobile manipulator's error on the assembly workspace.

From the represented scheme, it is simple to infer that the translation and orientation errors of the mobile manipulator have a direct correspondence on the assembly workspace. Additionally, the orientation error of the mobile platform creates further translation errors on the assembly workspace. Finally, it is also clear that this error propagation is amplified by the distance that the mobile platform is set to stop from the assembly location (represented by l in Figure 4).

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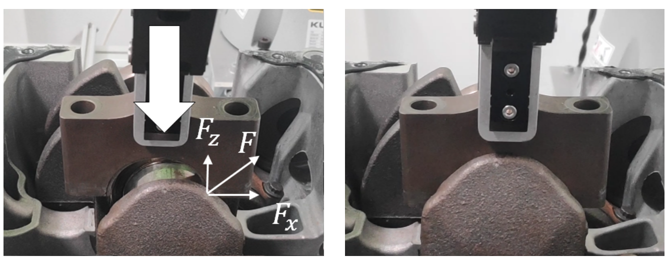
IV. Force Control Based Assembly

The inherent compliant characteristics and tools of the manipulator were explored intending to develop compliant search strategies to surpass positional uncertainties at the assembly level. These strategies were then combined to create compliant heuristics to surpass the errors of the considered use case, culminating on a successful assembly task.

A. Event-based search strategies

The first developed compliant strategy, **direct impedance control convergence**, intends to exploit the inherently convergent characteristic of some assembly tasks, in which the contact forces between the components are enough to correct the present errors on, at least, one degree of freedom. The use of impedance control mode is essential for this strategy, as the manipulator must be able to react to the contact forces between workpieces and deviate from its predetermined path accordingly. Figure 5 shows an example of this strategy, where the contact force component F_x is responsible for the correction of the position of the bearing cap along a cylindrical surface.

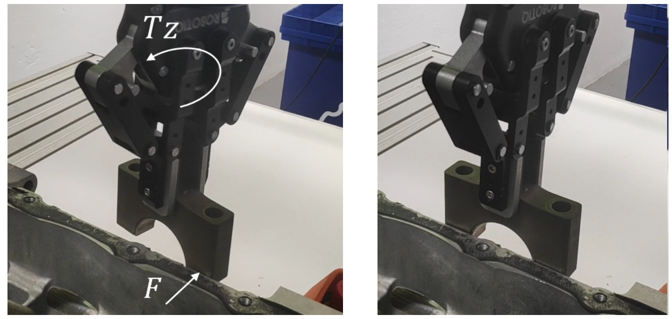


(a) Contact forces responsible for assembly convergence. (b) Result of the natural convergence strategy.

Fig. 5. Example of the direct impedance control convergence strategy.

Another developed strategy, **orientation correction using impedance control**, entails the correction of the orientation by aligning the manipulator's end effector with a predetermined surface within the assembly workspace. The correction of orientation is achieved by forcing a collision between the gripped component and the defined surface, while the manipulator is under impedance control with the stiffness of the rotation axis set to a significantly lower value than the remaining degrees of freedom. Figure 6 shows an example of this strategy being executed.

Similarly, it is possible explore the position of a fixed component within the assembly station by probing the environment until a predetermined collision with the workpiece is detected. This strategy, **environment exploration through collision detection**, allows the complete correction of translation errors, whenever the orientation is known with precision. However, if orientation errors are also present, the trajectory of the probing motions will be altered, impacting the effectiveness of this strategy. As such, whenever orientation uncertainties are present, the environment exploration strategy can only reduce the present translation errors, instead of fully correcting them.



(a) Orientation correction torque (T_z) resulting from contact force (F). (b) Result of correction - component aligned with surface.

Fig. 6. Example of orientation correction using impedance control.

Finally, intending to explore the 'Cartesian impedance controller with overlaid force oscillation', a **blind search using oscillations** strategy was developed. This mode allows the implementation of positional oscillations on one degree of freedom by overlaying a force to the impedance controlled system. Due to the nature of these oscillations, the resulting contact forces on that degree of freedom will never surpass the selected overlaid force, which is crucial for assembly operations. As such, these blind search routines can be executed to surpass relatively small errors in the assembly workspace.

B. Compliant heuristics

The considered robotic based assembly use case employs a mobile platform to carry the manipulator and a fixed platform where the assembly tasks are performed. Since both these stations have a constant height, the uncertainties present in the assembly operation are constrained to a plane parallel to the shop floor. Figure 7 shows the considered reference frame for the quantification of the positioning uncertainties. Using this reference frame, the uncertainties of the considered use case are limited to the ${}_x\mathrm{O}_y$ plane, namely, translation errors along x and y and rotation errors around z.

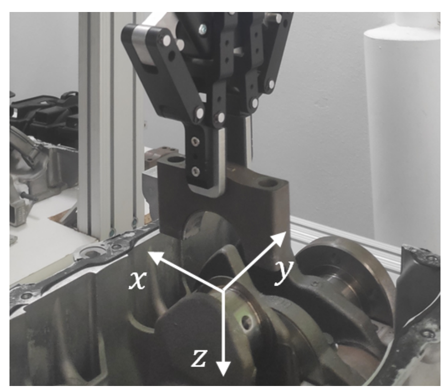


Fig. 7. Assembly reference frame.

The strategies presented in the previous Subsection were combined into compliant heuristics, with the goal of surpassing the positional uncertainties in the ${}_x\mathrm{O}_y$ plane and, ultimately, achieve a successful assembly operation.

The first developed method, **oscillation method**, mainly uses the 'blind search using oscillations' strategy with the intent of surpassing small positional errors. This approach executes a continuous vertical motion while employing the different oscillations and control modes required to complete the assembly task. Firstly, it performs an oscillation along the y axis to correct the error of this degree of freedom, resulting in the insertion of one extremity of the bearing cap inside the respective slot. Subsequently, an oscillation is made around the z axis, while using a low stiffness value for the x axis. This translates in an orientation correction through oscillation (to ensure that the bearing cap fully enters the required slot) and a simultaneous natural impedance convergence along the x axis (as represented in Figure 5). The different error correction phases of this method can be observed in Figure 8.

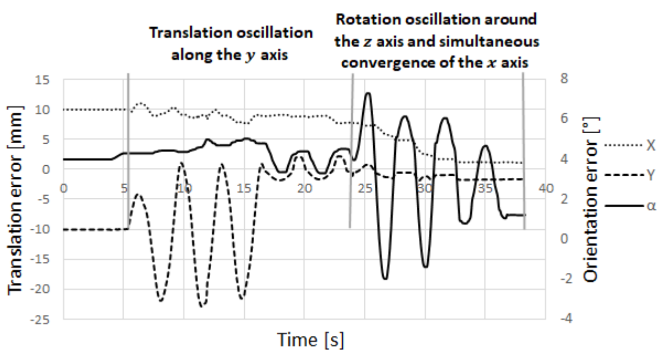


Fig. 8. Example of the error correction during the oscillation method.

The admissible positional errors of the aforementioned oscillation method may be increased by complementing it with a correction of either translation or orientation, through the 'environment exploration through collision detection' or the 'orientation correction using impedance control' strategies, respectively. These different approaches were the basis for the development of two more heuristics: **oscillation method complemented by environment exploration** and **oscillation method complemented by orientation correction**, which use the lateral surface of the engine block to perform the necessary corrections (similarly to the operation performed in Figure 6). Theoretically, the employment of these previous strategies should be enough for the complete correction of the translation and orientation errors. However, since the lateral wall of the engine block is not completely flat (it contains large irregularities), these strategies are not enough for the full correction of the present errors. Instead, they are used to decrease the uncertainties to a magnitude within the limits of the oscillation method, which is then performed to complete the assembly operation.

Finally, the last developed search method, **environment exploration complemented by orientation correction**, combines the 'environment exploration through collision detection' and the 'orientation correction using impedance control' strategies to fully surpass the present uncertainties. Once again, the irregularness of the lateral engine block surface means that the complete error correction cannot be achieved by just one cycle of orientation correction and environment exploration. Thus, this heuristic employs an iterative approach, where the error correction cycle is executed until the engine block's position relative to the manipulator is fully determined. After this routine is performed, the positional uncertainties of the assembly station are fully eliminated and, thus, the assembly operations can be directly performed.

V. Results

The developed force-based compliant heuristics were tested with the crankshaft bearing cap assembly use case. On a first stage, the tests were performed on a structured work environment, where no positional uncertainties of the components were present. This approach allowed specific assembly errors to be imposed on the assembly workspace, which was crucial for accurate testing of the search routines.

Moreover, it is important to emphasize that the developed routines, when performed directly on the assembly component, are reliant on its geometric characteristics. As an example, the performance of the oscillation method is reliant on the assembly tolerance and geometric characteristics of the workpieces, whereas the performance of the orientation correction and environment exploration method is reliant on the used surfaces for the probing motions. As such, the results showcased in this Section are valid for the particular use case at hand.

Intending to assess the limits of each developed heuristic, a methodical testing procedure was defined, where the imposed values of error were progressively increased and each developed routine was executed. Table I displays the results obtained with this procedure.

TABLE I
ERROR LIMITS OF THE COMPLIANT HEURISTICS IN THE ASSEMBLY WORKSPACE

	$\mathbf{x_A}[\mathrm{mm}]$	$\mathbf{y_A}[\mathrm{mm}]$	$\alpha_\mathbf{A}[°]$
Oscillation method	$[-10, 10]$	$[-10, 10]$	$[-4, 4]$
Oscillation method complemented by environment exploration	$[-30, 30]$	$[-30, 30]$	$[-4, 4]$
Oscillation method complemented by orientation correction	$[-10, 10]$	$[-10, 10]$	$[-20, 20]$
Environment exploration complemented by orientation correction	$[-30, 30]$	$[-30, 30]$	$[-20, 20]$

All the developed heuristics were successful at overcoming a certain degree of positional uncertainties in the assembly workspace, culminating on a successful assembly operation of the bearing cap. As expected, the oscillation method was the routine that showed potential to overcome smaller uncertainties, being able to surpass translation errors of up to $\pm 10\,\mathrm{mm}$ in both the x and y axis (a total of $14.1\,\mathrm{mm}$) when the orientation errors are limited to $\pm 4°$.

Moreover, it is clear that the approaches of complementing the oscillation method with a previous correction were effective at improving its capability of overcoming both translation and orientation errors. Finally, the environment exploration complemented by orientation correction method showed the best potential for the correction of larger errors. This method also has the upside of fully locating the assembly station position (total elimination of uncertainties, which allows the assembly of multiple components with just one routine), whereas the methods culminating in the oscillation strategy do not (they only mitigate uncertainties for a single assembly).

The performed tests also showed that if the orientation uncertainty changes, the capability of the search methods will be impacted. As an example, if an orientation uncertainty within the range of $[-6, 6]°$ is used, the oscillation method can only surpass translation errors of $[-9, 9]$ mm on both the x and y axis. On the other hand, if there are no orientation uncertainties, this method is able to surpass translation errors of up to $[-13, 13]$ and $[-12, 12]$ mm on the x and y axis, respectively.

Nevertheless, as it was demonstrated by Figure 4, the effect of the orientation errors of the mobile manipulator on the perceived position of the assembly space means that a direct correspondence cannot be done between both workspaces. In fact, since the orientation errors of the mobile manipulator will result in further translation errors on the assembly workspace, it is expected that the capability of the presented heuristics to surpass positioning errors of the mobile manipulator is actually lower than the results showcased in Table I.

For this reason, an effort was made to try and minimize the orientation errors of the mobile platform, even if at a cost of slightly higher translation errors. Preliminary tests showed that the developed mobile platform had enough positioning accuracy to guarantee orientation errors of no more than $\pm 1°$. Intending to increase the safety and robustness of the implemented system, an orientation uncertainty range of $\pm 2°$ was assumed. This consideration was used for the testing of the compliant heuristics, with the final mobile manipulator arrangement, as to assess their capability of surpassing the errors arising from the positioning of the mobile platform. The obtained results are displayed in Table II (the oscillation method complemented by orientation correction was not included as it was specifically developed to overcome higher orientation uncertainties than the ones considered for this use case).

The obtained results show that both the 'oscillation method complemented by environment exploration' and the 'environment exploration complemented by orientation correction' can be implemented successfully for the whole orientation error range of $\pm 2°$, showing great potential for the considered use case. Moreover, it is important to underline that the increased capability of the latter to surpass translation errors (when compared to the values displayed in Table I) is related to the limitation of orientation errors to drastically smaller values than what the method was originally developed to overcome ($\pm 2°$ as opposed to $\pm 20°$).

TABLE II
ERROR LIMITS OF THE COMPLIANT HEURISTICS IN THE MOBILE PLATFORM WORKSPACE

	$\alpha_R = [-1, 1]°$		$\alpha_R = [-2, 2]°$	
	x_R[mm]	y_R[mm]	x_R[mm]	y_R[mm]
Oscillation method	[-1.3, 1.3]	[-9.9,10]	-	-
Oscillation method complemented by environment exploration	[-21.3, 21.3]	[-29.9, 30]	[-12.6,12.6]	[-29.7, 30]
Environment exploration complemented by orientation correction	[-51.3, 51.3]	[-59.9, 60]	[-42.6,42.6]	[-59.7, 60]

Regarding the 'oscillation method', the results support that it can only be reliably employed for low orientation errors of the mobile platform ($\leq 1°$). However, since all the performed tests resulted in a successful assembly of the bearing cap using this method, the preliminary assessment that the mobile platform had an accurate positioning system that guarantees extremely low rotation errors was supported. Nevertheless, this method is being implemented on the limits of its capabilities, meaning that if abnormal factors cause the robot to approach the assembly position with slightly larger errors, the routine will most likely fail.

VI. GENERALIZATION

The proposed compliant heuristics are reliant on the geometry of the used assembly workpieces and, as such, cannot be directly integrated with other assembly stations. Therefore it is crucial to establish how these force-based methods could be integrated in general assembly stations.

Since the oscillation method uses blind search routines to accomplish the assembly task, it is generic enough to be adapted to other assembly operations with only a few calibrations (oscillated degrees of freedom and their respective amplitude).

On the other hand, the environment exploration method is much more reliant on the considered assembly task as it requires fixed surfaces within the assembly station to perform the probing motions and fully locate the station. However, since the properties of these surfaces (namely their size and flatness) have an influence on the performance of the heuristic, some assembly stations may not meet these requirements, impacting the viability of the proposed routine. This limitation can be circumvented by mounting an external accessory composed of two flat orthogonal surfaces on a fixed location relative to the assembly station, with the intention of using it as the contact point for the required probing motions. Moreover, this strategy allows the optimization of the geometric characteristics of the used surfaces, allowing the planar errors to be corrected by just two probing motions, instead of the iterative cycle necessary for irregular surfaces (such as in the presented use case).

Another crucial characteristic is the capability of each developed heuristic to fully eliminate the present uncertainties. As it can be seen in the example shown in Figure 8, the search methods culminating on an oscillation strategy do not fully eliminate the uncertainties of the assembly station (there is still a residual error present at the end of the routine). Instead, these methods reduce the errors to within the tolerance range of the performed assembly task, which means that if multiple components are to be assembled on a given station using these methods, the routine must be performed for every assembled component. On the other hand, the environment exploration with orientation correction method is able to fully eliminate the present uncertainties, which allows it to perform multiple assembly tasks with just one search routine.

VII. Conclusions

The present article described several force control strategies to surpass the positional and rotational uncertainties associated with mobile assembly platforms. Several search heuristics were showcased, underlining the strengths and drawbacks of each one when applied for use cases within the automotive industry.

The oscillation method showed potential to surpass small positional errors. Even though it was successfully implemented, it is working close to the limits of its capabilities, which means that if abnormal conditions result in larger positional errors of the mobile platform, the routine may fail. For these situations, the oscillation method can be complemented by a previous environment exploration with the intent of improving its overall robustness. Since this method needs to be performed for each assembly operation, its cycle time is only economically viable in stations with a small number of assembly tasks.

In turn, the method of environment exploration complemented by orientation correction showed the best potential to surpass larger positional uncertainties. Furthermore, since this method fully eliminates the positional uncertainties of the station, it is essential to ensure the economical viability of multiple assembly tasks performed in the same station. Even though this approach cannot be directly translated to other use cases, a generalization strategy using an external accessory was proposed, allowing it to be optimally implemented in any station.

Force-based routines can also be used to evaluate whether an assembly operation was completed successfully, which is crucial for the development of flexible and robust mobile assembly stations. This evaluation mechanism was implemented in the considered use case, allowing the system to adapt its behaviour in case of a failed assembly task.

Finally, the obtained results underlined the importance of the orientation errors in the positioning of the mobile platform, as the value of this error amplifies the translation uncertainties in the assembly workspace. For this reason, the orientation errors of the mobile station should be minimized whenever possible.

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