Operating articulated objects with force sensitive mobile manipulators

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Abstract—**Here we present an approach to manipulate a range of articulated objects using a mobile robot equipped with a force sensitive robotic arm. Our system is designed to operate based on programmable rough estimates of initial movement or even without any a priori knowledge at all. We use a manipulability criterion in conjunction with active compliance to plan and execute the desired task.**

I. Introduction

Assistant robots represent a category of mobile manipulators. They are envisioned to perform tasks in collaboration with human workers or at least within the same working environment [1]. In shared environments a mobile manipulator may be required to operate mechanisms that were designed for human operators. Those mechanisms are manifold and reach from doors, over drawers to machine hatches. Due to the high number of different mechanisms it is neither convenient to create kinematic models nor to teach them in advance. This leads to the necessity of generic algorithms which are capable of manipulating unknown or only partly known mechanisms. Execution of unknown tasks is not entirely new. But up to now, there are no sufficient capabilities to handle unknown mechanisms by robots.

Therefore, we present our advances for a generalized framework for operating unknown mechanisms with a mobile manipulator. In this report we will focus on three main parts of this framework: a) Determination of an initial configuration of the mobile manipulator, b) Determination of the opening direction of the mechanism and c) Successive manipulation of the mechanism.

The presented methods are applied to an assistant robot called ANNIE designed by the Fraunhofer Institute for Factory Operation and Automation in Magdeburg, Germany. ANNIE consists of a mobile platform with four Mecanum wheels which enable omnidirectional movements. As a manipulator, a LWR4+ by KUKA with seven degrees of freedom is employed which provides a position and a torque interface as control input. Furthermore, the manipulator is equipped with Robotiq's Three-Finger-Gripper used as endeffector.

II. Related Work

Several researchers have addressed the problem of manipulating unknown mechanisms with a mobile manipulator. However, most of them focus on specific mechanisms such as doors [2]–[6].

In [2] a mobile manipulator with a compliant arm is employed to open doors by planning coordinated motions between robot arm and mobile platform. Therefore, the position of the door handle and the door hinge are required, which might be hard to determine in many cases. However, it could be shown that a mobile manipulator with a compliant arm is capable of manipulating a mechanism with uncertainties about its kinematics.

The approaches presented in [3]–[5] don't rely on additional knowledge about the door. They however require a firm grasp between endeffector and door handle, so that there is no relative movement between endeffector frame and task frame. By that a constant movement vector in endeffector frame can be determined in order to manipulate the mechanism. A firm grasp, however, is not always possible. Furthermore it imposes additional constraints on the movability of the manipulator. The requirement of a firm grasp is relaxed in [6]. In order to be able to determine movement direction of the door the task frame is determined by tracking the door handle. This however can be difficult in situations with poor lighting conditions or occultation.

In [7] an approach is presented which is not only capable of opening doors but drawers as well. By tracking the position of the endeffector over time and fitting this information to the equation of a circle, the further movement of the mechanism is estimated. In the case of a prismatic joint this will lead to a circle with a relatively large radius. This allows to differentiate between prismatic and revolute joints by examining the magnitude of the estimated radius. The method is extended in [8] by integrating the mobile base into the manipulation task in order to enlarge the reachable workspace of the manipulator. This approach however requires knowledge about the plane in which the mechanism moves in order to apply the equation of a circle.

In [9] a framework for opening doors and drawers has been presented which utilizes probabilistic methods to match the movement of the mechanism to predefined kinematic models in order to determine the subsequent motion. This can be seen as a generalized approach for opening mechanisms with one degree of freedom. However, important features such as the placement of

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the mobile platform in front of the mechanism or the determination of the opening direction of the mechanism haven't been regarded.

The approaches presented above solely consider the kinematic of the mechanism as unknown. However, as shown in [10] there is a large variety of mechanisms with similar kinematics, but with a notable difference in forces that need to be applied to manipulate the mechanism. For that reason the dynamics can't be discounted in order to be able to manipulate many different mechanisms. Therefore, we present an approach which is capable of manipulating unknown mechanisms with one degree of freedom such as doors, drawers and hatches but also mechanisms such as cranks. Furthermore, we will assume mechanisms with varying dynamics and tackle the questions on how to position the robot in front of the mechanism and how to determine the initial opening direction of the mechanism as these information can't be predetermined.

III. Problem Statement

The manipulation of an articulated object is a complex task for a robotic system, especially without knowledge about the mechanism's kinematic. Therefore, the problem was divided into multiple subtasks. Below, three of these subtasks will be described as they appear to be the most relevant and challenging in order to fulfill the given manipulation task.

A. Determination of an initial configuration

To manipulate a mechanism the robot needs to establish a physical connection with it. Therefore a grasp is planned which is described in world coordinate frame. The grasp pose defines the placement of the endeffector in order to establish a connection. Therefore, the mobile platform needs to be placed in front of the mechanism so that the grasp is in reachable range of the manipulator. The mapping between the grasp pose and the pose of the mobile platform is not distinct since the grasp can be reached through an infinite number of different configurations of the robot. These configurations are composed by position (x,y) and orientation γ of the mobile platform as well as joint position $\boldsymbol{q} \in \mathbb{R}^7$ of the manipulator. However, not every configuration is suitable for the given task. Therefore it is necessary to resolve the given ambiguity in a sophisticated way.

B. Determination of an initial movement direction

Another ambiguity occurs while trying to move the mechanism. As neither the type nor the position of the joint of the mechanisms is known, the direction in which the mechanism can be moved can't be determined without additional knowledge. However, it is possible to reduce the number of feasible directions by including information obtained through sensor readings. Still, even for a human it can be difficult to determine the opening direction of a mechanism without evaluating different possibilities. Therefore a strategy needs to be developed in order to reduce the search space as far as possible and evaluate the remaining space in a comprehensive way within a feasible time frame.

C. Successive manipulation of the mechanism

Without knowledge about the mechanisms kinematics it is impossible to plan a motion trajectory for the given task in advance. Therefore a successive manipulation approach is mandatory. By tracking the movement of the endeffector while manipulating, the further motion of the mechanism can be estimated consecutively. Since these estimations will be erroneous, a compliant behavior for the manipulator is required in order to compensate for inaccuracies. Therefore, a custom control strategy for the given setup and an estimator for the mechanism's path of motion needs to be developed.

IV. Approach

In order to approach the problems stated in the previous section the following methods have been developed:

A. Determination of an initial configuration

To resolve the ambiguity of the robots initial configuration it is necessary to evaluate different possibilities. Therefore a measure of quality is needed that can determine the capability of the robot to perform the given task. With this measure of quality it is possible to decide which initial configuration leads to higher chances of success and is thus desirable.

As the kinematic of the mechanism is unknown, only the capabilities of the mobile manipulator can be taken into account. In addition, as the mobile platform is able to perform omnidirectional movements the measure of quality is mainly defined by the state of the manipulator. Therefore, it is useful to configure the manipulator in a way that it is far away from singular configuration, joint limits and obstacles, but still is able to reach a desired grasp.

The proximity to singular configurations can be described with the manipulability m introduced by Yokoshiva [11], where $\boldsymbol{J}$ denotes the Jacobian of the given manipulator.

$$m = \sqrt{\det\left(\boldsymbol{J}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})^T\right)} \tag{1}$$

The manipulability is widely used to describe the movability of a manipulator in Cartesian space. Still, its interpretation can be misleading as it combines translation and rotational movement. Different approaches address this problem [12], [13]. However, we propose to separately calculate the manipulability for the translational $\boldsymbol{J}_t$ and rotational $\boldsymbol{J}_r$ part of the Jacobian as shown in (2). Hence, we were able to achieve more intuitive results regarding the given task.

$$m = \sqrt{\det\left(\boldsymbol{J}_t(\boldsymbol{q})\boldsymbol{J}_t(\boldsymbol{q})^T\right)} \cdot \sqrt{\det\left(\boldsymbol{J}_r(\boldsymbol{q})\boldsymbol{J}_r(\boldsymbol{q})^T\right)} \tag{2}$$

In order to improve the validity, the distance d between the endeffector and detected obstacles was incorporated into the measure of quality using a normalized cost function $P(d) \in [0,1]$. Thus, configurations that are further away from possible collisions of the robot are preferred. The collision between different parts of the manipulator is prevented by joint limits. As those limits also restrict the movability of the manipulator, they need to be incorporated into the measure of quality. Their integration however isn't straight forward because of the redundancy of the manipulator. Even if a joint limit is reached, the ability to perform Cartesian motion might not be restricted. Thus, it is more suitable to penalize the Jacobian than the manipulability measure because the Jacobian takes the manipulators redundancy into account. Therefore the column i of the Jacobian is penalized according to the distance to the limit of joint i, which leads to the final equation for the manipulability as shown in (3). The penalized Jacobian is denoted with $\tilde{\boldsymbol{J}}$.

$$m = \sqrt{\det\left(\tilde{\boldsymbol{J}}_t(\boldsymbol{q})\tilde{\boldsymbol{J}}_t^T(\boldsymbol{q})\right)} \cdot \sqrt{\det\left(\tilde{\boldsymbol{J}}_r(\boldsymbol{q})\tilde{\boldsymbol{J}}_r^T(\boldsymbol{q})\right)} \cdot P(d) \qquad (3)$$

By evaluating possible configurations for a given grasp with the developed measure of quality, the ambiguity can be resolved.

B. Determination of an opening direction

In order to determine the initial movement direction of the mechanism, additional information needs to be generated. In [4] the detection of the door plane is proposed. By placing a normal vector onto this plane the movement direction can be determined. That approach however can be difficult to transfer to other mechanisms, such as sliding doors. Furthermore, it imposes new challenges when considering glass doors or poor lighting conditions. Therefore, we propose an approach that doesn't rely on additional sensors and still is robust and transferable to a broad range of different robots.

Even without sight, a human can determine the movement direction of an unknown mechanism within a few trials as long as there is a physical connection. That is because the handle of mechanism is mounted in a way that it allows a good transmission of forces in the direction in which the mechanism can be moved. Therefore, possible directions can be reduced to a plane by taking the orientation of the grasp into account as shown in Fig. 1. Still, there are infinitely many possibilities. Based on the compliance behavior of the robot, which will be presented in detail in the next section, we can evaluate different possible directions without harming the mechanism or the manipulator. Furthermore, it is not necessary to find the exact direction as the manipulator will move the mechanism even if there is a small offset between the estimated and the true direction. Because of that it is possible to discretize the remaining space with a finite number of equally spaced directions inside the plane. For our setup a discretization with eight direction vectors was sufficient to determine the true opening direction of the mechanism. Thus, within the identified plane direction vectors are placed every 45°. In order to take the dynamics of the mechanism into account, we started to evaluate the possible direction with a small stiffness and increased the applied forces with every run until an obvious movement of the mechanism could be determined.

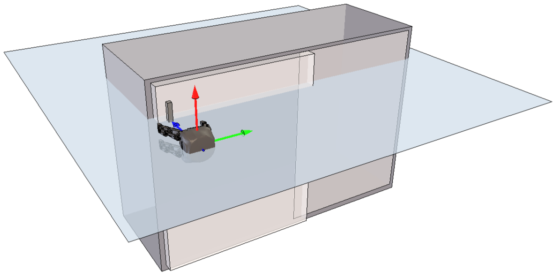

Fig. 1: Initial movement plane of the mechanism

C. Successive manipulation of the mechanism

As the path of motion of the mechanism is unknown a new direction vector needs to be estimated successively. In contrast to the determination of the initial vector, the recorded motion of the mechanism can be added to the estimation. When only considering mechanisms that can be modelled by one joint, the motion trajectory is either a line or a circle depending on the joint type. As shown in [7] both trajectories can be approximated with an equation of a circle. This approach however requires knowledge about the plane in which the mechanism is moving. In order to generalize this approach it is necessary to determine that plane. Therefore it is defined by the x- and y-axis of the coordinate system Σ_e which has its origin in the grasp position and its x-axis pointing in the direction of the initial movement vector of the mechanism. By applying these constraints, coordinate system and plane can only be rotated around the x-axis of Σ_e. However, this rotation is enough to determine the true plane in which the mechanism is moving. In the following the rotation is denoted with ϕ. While tracking the position of the endeffector $\boldsymbol{x}_t \in \mathbb{R}^3$ the angle of rotation can be determined. In case the true motion plane is found, the tracked positions lie completely inside that plane and thus won't have a defection in z-direction when described in Σ_e. That leads to the following cost function for optimizing the rotation of the motion plane.

$$\phi^* = \underset{\phi}{\arg\min} \left\| \sum_{k=0}^{m} (0 \;\; \sin\phi \;\; \cos\phi)^e \boldsymbol{x}_t(k) \right\| \qquad (4)$$

When describing the tracked motion $\boldsymbol{x}_t(k)$ in Σ_e the equation of a circle can be fitted to data projected to the xy-plane and the movement direction can be determined by calculating the tangent of the circle equation. Still, as that is only an estimation, a control scheme is required which realizes a compliant behavior of the manipulator in order to compensate for the inaccuracies. Therefore a modified Cartesian impedance controller [14] with a desired Cartesian stiffness $\boldsymbol{K}_d$ and a desired Cartesian damping $\boldsymbol{D}_d$ was implemented. In order to utilize the manipulators torque interface, the Cartesian stiffness and damping was converted into equivalent joint space stiffness $\boldsymbol{K}_q$ and damping $\boldsymbol{D}_q$ which are configuration dependent and can be determined using the manipulator's Jacobian.

$$\boldsymbol{D}_q(\boldsymbol{q}) = \boldsymbol{J}(\boldsymbol{q})\boldsymbol{D}_k\boldsymbol{J}(\boldsymbol{q})^T \qquad (5)$$

$$\boldsymbol{K}_q(\boldsymbol{q}) \approx \boldsymbol{J}(\boldsymbol{q})\boldsymbol{K}_k\boldsymbol{J}(\boldsymbol{q})^T \qquad (6)$$

The relation described in (6) only holds for a small offset around a desired Cartesian equilibrium point $\boldsymbol{x}_d \in \mathbb{R}^6$. As pictured in Fig. 2 the control scheme was divided into a Cartesian part and a joint space part which allows complex calculations in the low frequency Cartesian part and a high frequency torque controller in the joint space part in order to ensure stability. That requires calculating a joint space equilibrium $\boldsymbol{q}_d \in \mathbb{R}^7$ from the desired Cartesian equilibrium point using the inverse kinematics of the manipulator. This however enables explicit exploitation of the redundancy of the manipulator, as the null space can be utilized using the redundancy parameter ψ in order to avoid poor configurations such as singularities or joint limits. Without external forces the endeffector will stall in the desired equilibrium point, but will also be compliant according to the desired stiffness and damping. With the described control scheme the mechanism can be manipulated by shifting the Cartesian equilibrium point along the determined movement direction of the mechanism until the end of range of the manipulator is reached. Therefore, the mobile platform was integrated into the manipulation task in order to enlarge the reachable space of the manipulator. As soon as the measure described in section IV-A is below a threshold, the mobile platform is moved in the direction of increasing manipulability and the offset due to the movement is added to the desired equilibrium point in order to decouple the platform movement from the actual manipulation. By combining this control strategy with the other presented approaches into a generalized framework, unknown mechanisms can be manipulated autonomously.

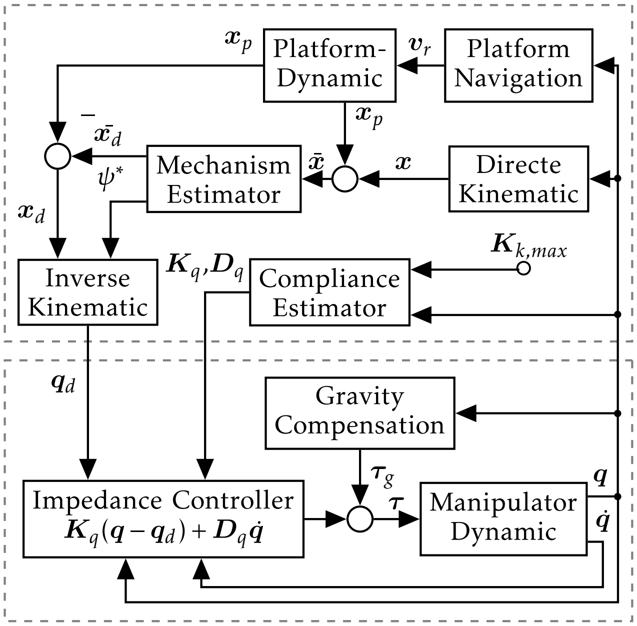

Fig. 2: Modified impedance controller with integrated mechanism estimator and platform navigation

V. Conclusion and Outlook

The presented work is a first attempt for a generalized framework that is capable of operating unknown mechanisms with a mobile manipulator. However, the current approach demands a constant physical connection between the manipulator and the mechanism. This can limit the capabilities especially when considering obstacles such as walls and can thus lead to unsuccessful attempts even if the robot is theoretically capable of performing the task. Therefore, we envision complementing the presented control scheme with a higher level planner that is capable of performing reconfigurations in order to circumvent possible dead locks.

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