Virtual Mechanism Approach for Dual-arm Manipulation

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Abstract: We propose a novel control approach for cooperative dual-arm object manipulation. Our scheme has three typical features: (1) the two arms with the object together form a new kinematic chain, where the base of the second arm is the end-effector of the new robot; (2) the object between the robots is defined as a virtual mechanism, therefore manipulating the object is accomplished by controlling the virtual mechanism; (3) the proposed scheme allows cooperative dual-arm systems performing a task while moving on mobile platforms. The proposed algorithm is verified with experiments on a dual-arm system with Kuka LWR robots, and simulations with 2 different robots: Kuka LWR on a fixed support and Mitsubishi PA10 robot on a mobile platform Nomad XR400.

1 INTRODUCTION

There are many advantages and benefits using dual-arm robots. For example, two arms can perform independent or coordinated complex bimanual assembly tasks without the aid of fixtures or jigs, transfer voluminous and heavy objects. Cooperative manipulation of objects with a dual-arm robot provides more flexible and versatile task execution than the manipulation of object with a single arm robot.

Control policies for cooperative manipulators can be roughly divided into two categories: symmetric formulation and task-oriented formulation. The kinetostatic symmetric formulation proposed by (Uchiyama and Dauchez, 1992) is based on mappings between forces and velocities at the tightly grasped object and their counterparts in the ”virtual sticks”. The major problem in this formulation is that the task-space kinetostatic variables are often unsuitable for the description of the cooperative task. The task-oriented formulation proposed by (Caccavale et al., 2000) and (Chiacchio and Chiaverini, 1998) fully characterises a cooperative operational space and allows the user to specify the task in terms of geometrically meaningful motion variables defined at the position/orientation level. The main advantage of defining the cooperative task-space is that the control can be applied to flexible objects and to nonrigid grasps. In both formulations above, the cooperative task is described by the absolute position and orientation of the objects origin, and the relative position and orientation between the arm end-effectors. However, many cooperative tasks that can be performed with a dual-arm robot are independent of absolute position and orientation of the object. Example of such a task are screwing a cap on the bottle, playing a harmonica, etc.

In industrial practice cases when robots are placed on a conveyor or on a vehicle, are common. The control of cooperative manipulators performing a task when base of one robot is moving is not straightforward. (Khatib et al., 1996) proposed a dynamic coordination strategy for multiple mobile manipulator cooperation. (Osumi, 1996) proposed cooperative position controlled manipulators on mobile platforms as free joint mechanisms for achieving mechanical compliance in order to avoid excessive inner forces between the manipulators.

In this paper, a different approach for control the cooperative manipulators performing a task is proposed. Our approach is based on a representation of two robot arms together with the object, as an augmented kinematic chain. The base frame of this kinematic chain is located at the base frame of the first robot, while the end-effector is located at the base frame of the second robot. The task between the robot arms is defined as a virtual mechanism with arbitrary degrees of freedom (Nemec and Žlajpah, 2009). The task is performed by controlling the internal variables (joints) of the virtual mechanism.

The proposed formulation allows cooperative manipulators performing a task also in the case when their bases are moving on a conveyor or on a mo-

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bile platform, on a kinematic level using position controllers. Consider controlling an augmented chain, its end-effector reference is the base of the moving robot. The problem of excessive inner forces was solved using the compliance of the manipulator.

2 VIRTUAL MECHANISM APPROACH

Consider a system of two robots tightly grasping a rigid object. We model the contact of the robot end-effector with the object as a fixed link. Let n_i denote the number of joints for each robot (i=1,2), $\boldsymbol{q}_i$ the $(n_i \times 1)$ vector of joint variables, and $\mathbf{T}_i$ the homogeneous transformation including the end-effector position vector $\boldsymbol{x}_i$ and $\mathbf{R}_i$ the rotation matrix expressing the end-effector orientation. The end-effector velocity vector $\dot{\boldsymbol{x}}_i$ is related to the joint velocity vector $\dot{\boldsymbol{q}}_i$ through the robot Jacobian matrix $\mathbf{J}_i(\boldsymbol{q}_i)$. All quantities are expressed in the base of the i-th robot.

The system with two robots and object is presented in the Fig. 1.

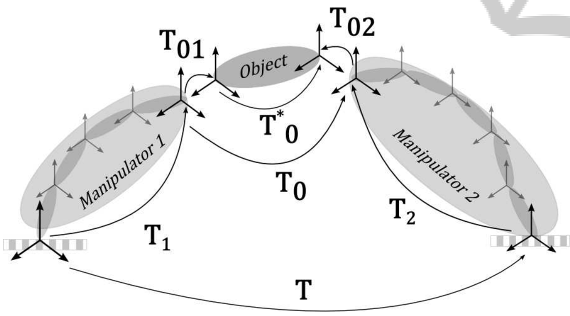

Figure 1: The two robots and the object form a new augmented kinematic chain.

The mapping between the object base frame and the end-effector frame of the first robot is represented by the transformation $\mathbf{T}_{01}$, which defines how the object is grasped by the first robot. Similarly, $\mathbf{T}_{02}$ defines the transformation from the end-effector of the object and the end-effector of the second robot. $\mathbf{T}_0^*$ is the homogeneous transformation of the virtual mechanism, and $\mathbf{J}_0$ is the Jacobian matrix of the virtual mechanism, which relates the joint velocity vector $\dot{\boldsymbol{q}}_0$ with end-effector velocity vector $\dot{\boldsymbol{x}}_0$ of the virtual mechanism. Consider that n_0 represents the number of degrees of freedom (DOF) of the virtual mechanism.

We can write the homogeneous transformation for the above system as a open kinematic chain from base of first robot to the base of the second robot as

$$\mathbf{T} = \mathbf{T}_1\mathbf{T}_0\mathbf{T}_2^{-1} \tag{1}$$

where

$$\mathbf{T}_0 = \mathbf{T}_{01}\mathbf{T}_0^*\mathbf{T}_{02} = \begin{bmatrix} \mathbf{R}_0 & \mathbf{x_0} \\ \mathbf{0} & 1 \end{bmatrix} \tag{2}$$

Assume that virtual mechanism base frame is located at the end-effector frame of the first robot. Therefore the transformation $\mathbf{T}_{01}$ is unit matrix. The second robot end-effector frame corresponds to rotated coordinate frame of the virtual mechanism end-effector. We can rewrite Eq. (2) as

$$\mathbf{T}_0 = \mathbf{T}_0^*\mathbf{T}_{02} = \mathbf{T}_0^* \begin{bmatrix} \mathbf{R}_x(\pi) & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix} \tag{3}$$

The homogeneous transformation Eq. (1) is composed of the rotation matrix and the position vector.

$$\mathbf{T} = \begin{bmatrix} \mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T & \mathbf{x_1} + \mathbf{R_1}\mathbf{x_0} - \mathbf{R_1}\mathbf{R_0}\mathbf{R_2^T}\mathbf{x_2} \\ \mathbf{0} & 1 \end{bmatrix} \tag{4}$$

The two robots and the object form a new kinematic chain. Consider this kinematic chain as a virtual robot. Let $\dot{\boldsymbol{x}}_r$ denote the end-effector velocity and $\dot{\boldsymbol{q}}_r$ the joint velocities of the virtual robot. Mapping between them is described in the well known forward kinematic law

$$\dot{\boldsymbol{x}}_r = \mathbf{J}_r\dot{\boldsymbol{q}}_r \tag{5}$$

Above expression requires knowledge of Jacobian matrix $\mathbf{J}_r$ of the virtual robot, where the joint velocity vector is

$$\dot{\boldsymbol{q}}_r = \begin{bmatrix} \dot{\boldsymbol{q}}_1 \\ \dot{\boldsymbol{q}}_0 \\ \dot{\boldsymbol{q}}_2 \end{bmatrix} \tag{6}$$

2.1 Derivation of the Jacobian Matrix $\mathbf{J}_r$

The method proposed in this paper derives the Jacobian matrix $\mathbf{J}_r$ of the virtual robot with the time derivation of the homogeneous transform Eq. (4) of the virtual robot. In general, the Jacobian matrix can be split into the position part $\mathbf{J}_v$ and the orientation part $\mathbf{J}_\omega$.

$$\mathbf{J}_r = \begin{bmatrix} \mathbf{J}_v \\ \mathbf{J}_\omega \end{bmatrix} \tag{7}$$

Considering the fact that Jacobian matrix is a mapping from joint velocities to end-effector linear and angular velocities, it is possible to obtain $\mathbf{J}_v$ using the time derivative of the position vector $\mathbf{x}$ in the homogeneous transform Eq. (1).

$$\begin{aligned}\dot{\mathbf{x}} = {} & \dot{\mathbf{x}}_1 + \dot{\mathbf{R}}_1\mathbf{x_0} + \mathbf{R_1}\dot{\mathbf{x}}_\mathbf{0} - \dot{\mathbf{R}}_1\mathbf{R_0}\mathbf{R_2^T}\mathbf{x_2} - \\ & - \mathbf{R}_1\dot{\mathbf{R}}_0\mathbf{R}_2^T\mathbf{x_2} - \mathbf{R_1}\mathbf{R_0}\dot{\mathbf{R}}_\mathbf{2}^\mathbf{T}\mathbf{x_2} - \mathbf{R_1}\mathbf{R_0}\mathbf{R_2^T}\dot{\mathbf{x}}_\mathbf{2}\end{aligned} \tag{8}$$

The time derivative of rotation matrix $\mathbf{R}$ can be expressed with a skew-symmetric matrix $\mathbf{S}(\omega)$ (Spong et al., 2005) as

$$\dot{\mathbf{R}} = \mathbf{S}(\omega)\mathbf{R} \tag{9}$$

Using the proprieties of $\mathbf{S}$

$$\mathbf{S}(\omega)\mathbf{x} = \mathbf{S}(\mathbf{x})^{\mathbf{T}}\omega \tag{10}$$

and

$$\dot{\mathbf{R}^{\mathbf{T}}} = -\mathbf{R}^{T}\mathbf{S}(\omega) \tag{11}$$

we can rewrite Eq. (8) as

$$\begin{aligned}\dot{\mathbf{x}} = {} & \dot{\mathbf{x}}_1 + \mathbf{S}(\mathbf{R}_1\mathbf{x_0})\omega_\mathbf{1} + \mathbf{R_1}\dot{\mathbf{x}}_\mathbf{0} - \\ & - \mathbf{S}(\mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\mathbf{x_2})^{\mathbf{T}}\omega_\mathbf{1} - \mathbf{R_1}\mathbf{S}(\mathbf{R_0}\mathbf{R_2^T}\mathbf{x_2})^{\mathbf{T}}\omega_\mathbf{0} + \\ & + \mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\mathbf{S}(\mathbf{x_2})^{\mathbf{T}}\omega_\mathbf{2} - \mathbf{R_1}\mathbf{R_0}\mathbf{R_2^T}\dot{\mathbf{x}}_\mathbf{2}\end{aligned} \tag{12}$$

Next, using relations

$$\omega = \mathbf{J}_\omega\dot{\boldsymbol{q}} \tag{13}$$

and

$$\dot{\mathbf{x}} = \mathbf{J}_v\dot{\boldsymbol{q}} \tag{14}$$

The Eq. (12) yields the position part of the Jacobian matrix

$$\mathbf{J}_v = \left[\begin{array}{ccc} \mathbf{J_{v_1}} + \mathbf{A}\mathbf{J}_{\omega_1} & \mathbf{R}_1(\mathbf{J_{v_0}} - \mathbf{B}\mathbf{J}_{\omega_0}) & \mathbf{C}\mathbf{J}_{\omega_2} - \mathbf{D}\mathbf{J_{v_2}} \end{array}\right] \tag{15}$$

where

$$\begin{aligned}\mathbf{A} &= \mathbf{S}(\mathbf{R}_1\mathbf{x_0})^{\mathbf{T}} - \mathbf{S}(\mathbf{R_1}\mathbf{R_0}\mathbf{R_2^T}\mathbf{x_2})^{\mathbf{T}} \\ \mathbf{B} &= \mathbf{S}(\mathbf{R}_0\mathbf{R}_2^T\mathbf{x_2})^{\mathbf{T}} \\ \mathbf{C} &= \mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\mathbf{S}(\mathbf{x_2})^{\mathbf{T}} \\ \mathbf{D} &= \mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\end{aligned}$$

and $\mathbf{J_{v_i}}$ and $\mathbf{J}_{\omega_\mathbf{i}}$ are the position and orientation part of the Jacobian matrix of the i-th robot, respectively. The $\mathbf{J_{v_0}}$ and $\mathbf{J}_{\omega_\mathbf{0}}$ are the position and orientation part of the Jacobian matrix of the virtual mechanism.

Similarly we obtain the time derivative of the rotation matrix $\mathbf{R}$ of the homogeneous transform Eq. (4)

$$\dot{\mathbf{R}} = \dot{\mathbf{R}}_1\mathbf{R}_0\mathbf{R}_2^T + \mathbf{R}_1\dot{\mathbf{R}}_0\mathbf{R}_2^T + \mathbf{R}_1\mathbf{R}_0\dot{\mathbf{R}}_2^T \tag{16}$$

Using the Eq. (9), multiplying both sides of Eq. (16) on the right by $(\mathbf{R}_1\mathbf{R}_2\mathbf{R}_3)^{-1}$, using the orthogonality of the rotation matrix ($\mathbf{R}^{-1} = \mathbf{R}^T$) and the property of the skew-symmetric matrix

$$\mathbf{S}(\mathbf{R}\omega) = \mathbf{R}\mathbf{S}(\omega)\mathbf{R}^T \tag{17}$$

we get

$$\mathbf{S}(\omega) = \mathbf{S}(\omega_1) + \mathbf{S}(\mathbf{R}_1\omega_0) - \mathbf{S}(\mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\omega_2) \tag{18}$$

Since

$$\mathbf{S}(\mathbf{a}) + \mathbf{S}(\mathbf{b}) = \mathbf{S}(\mathbf{a}+\mathbf{b}) \tag{19}$$

as shown in (Spong et al., 2005). The following relation for ω is obtained from Eq. (18)

$$\omega = \omega_1 + \mathbf{R}_1\omega_0 - \mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\omega_2 \tag{20}$$

Using the Eq. (13) and substituting $\omega, \omega_1, \omega_0, \omega_2$ in Eq. (20) we get the orientation part of the Jacobian $\mathbf{J}_\omega$

$$\mathbf{J}_\omega = \left[\begin{array}{ccc} \mathbf{J}_{\omega_1} & \mathbf{R}_1\mathbf{J}_{\omega_0} & -\mathbf{R}_1\mathbf{R}_0\mathbf{R}_2^T\mathbf{J}_{\omega_2} \end{array}\right] \tag{21}$$

Combining Eq. (15) and Eq. (21) yields the Jacobian matrix of the whole system

$$\mathbf{J}_r = \left[\begin{array}{ccc} \mathbf{J}_{v_1} + \mathbf{A}\mathbf{J}_{\omega_1} & \mathbf{R}_1(\mathbf{J}_{v_0} - \mathbf{B}\mathbf{J}_{\omega_0}) & \mathbf{C}\mathbf{J}_{\omega_2} - \mathbf{D}\mathbf{J}_{\mathbf{v}_2} \\ \mathbf{J}_{\omega_1} & \mathbf{R}_1\mathbf{J}_{\omega_o} & -\mathbf{D}\mathbf{J}_{\omega_2} \end{array}\right] \tag{22}$$

which has dimensions $(6 \times p)$, where $p = n_1 + n_0 + n_2$.

3 CLOSED-LOOP VELOCITY CONTROL

The desired cooperative task-space trajectory is transformed into the corresponding joint motion for each robot using the inverse kinematic algorithm. Using the redundancy resolution at the kinematic level the control algorithm can be defined as

$$\dot{\boldsymbol{q}}_r = \mathbf{J}_r^{\#}\dot{\boldsymbol{x}}_r + \mathbf{N}\xi \tag{23}$$

where

$$\mathbf{J}_r^{\#} = \mathbf{W}^{-1}\mathbf{J}_r^T(\mathbf{J}\mathbf{W}^{-1}\mathbf{J}_r^T)^{-1} \tag{24}$$

is weighted generalised-inverse of the $\mathbf{J}_r$. $\mathbf{W}$ is the $(p \times p)$ weighting matrix. $\mathbf{N} = (\mathbf{I} - \mathbf{J}_r^{\#}\mathbf{J}_r)$ is a $(p \times p)$ matrix representing the projection into the null space of $\mathbf{J}_r$, and ξ is an arbitrary p dimensional vector (Nemec et al., 2007).

Reference for the calculation of $\dot{\boldsymbol{x}}_r$ was the position and orientation of the second robot base presented as the end-effector of the virtual robot in the coordinate frame $\mathbf{T}$. When the base of the second robot is fixed, this error manifests as error between robot end-effectors.

When performing a task in dual arm configurations, we have to specify the desired task as the motion of the virtual mechanism. In our formulation this can be accomplished using the extended task space and extended Jacobian. The extended Jacobian matrix is defined as

$$\mathbf{J}_e = \left[\begin{array}{c} \mathbf{J}_0^* \\ \mathbf{J}_r \end{array}\right] \tag{25}$$

Where

$$\mathbf{J}_0^* = \left[\begin{array}{ccc} \mathbf{0} & \mathbf{J}_0 & \mathbf{0} \end{array}\right] \tag{26}$$

The extended task space is

$$\dot{\boldsymbol{x}}_e = \left[\begin{array}{c} \dot{\boldsymbol{x}}_0 \\ \dot{\boldsymbol{x}}_r \end{array}\right] \tag{27}$$

The $\dot{\boldsymbol{x}}_0$ is velocity error of the task with the virtual mechanism. Inverse kinematics algorithm Eq. (23), with extended Jacobian matrix is

$$\dot{\boldsymbol{q}}_r = \mathbf{J}_e^{\#}\dot{\boldsymbol{x}}_e + \mathbf{N}_e\xi \tag{28}$$

A simple feed forward driven P velocity controller is employed to compensate for the linear velocity error of $\dot{\boldsymbol{x}}_e$, and quaternion controller to compensate for the rotational velocity error of $\dot{\boldsymbol{x}}_e$.

4 SIMULATION RESULTS

The proposed algorithm was tested on a system with two different robots performing cooperative task. The first robot is the Kuka LWR robot with 7 DOF, mounted on a fixed support, and the second robot is Mitsubishi PA10 robot mounted on a mobile robot Nomad XR4000.

The system is modelled as a augmented kinematic chain, where base of the Kuka LWR robot is the base of the virtual robot, while base of the mobile robot Nomad is the end-effector of the virtual robot.

The task is to wind the wool on a spool. This is a typical operation, where the absolute position of the object is not important to accomplish the task. For the task description three control variables are required; the translational motion along the z-axis and circular motion in the $x-y$ plane. The task is accomplished with controlling the virtual mechanism. Trajectory for the motion is defined in the coordinate frame $\mathbf{T}_0$.
In this case, we can define the virtual mechanism as a 3 DOF robot with prismatic joints. Thus, the virtual mechanism joint vector is the same as the task space vector

$$\boldsymbol{x}_0 = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \boldsymbol{q}_0 \tag{29}$$

Therefore, the Jacobian matrix equals

$$\mathbf{J}_0 = \frac{\partial \boldsymbol{x}_0}{\partial \boldsymbol{q}_0} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{30}$$

To demonstrate the flexibility of the proposed approach, the mobile robot was performing circular motion on a floor while performing the given task. The null-space matrix was chosen in order to preserve the conservative motion of the system (Nemec et al., 2007).

Simulation results show that the cooperative robots can effectively perform the given task while exploiting full redundancy of the system. The reference trajectory and the response are shown in Fig. 2 and Fig. 3.

The snapshots of 6 instances of the given task are presented in Fig. 4.

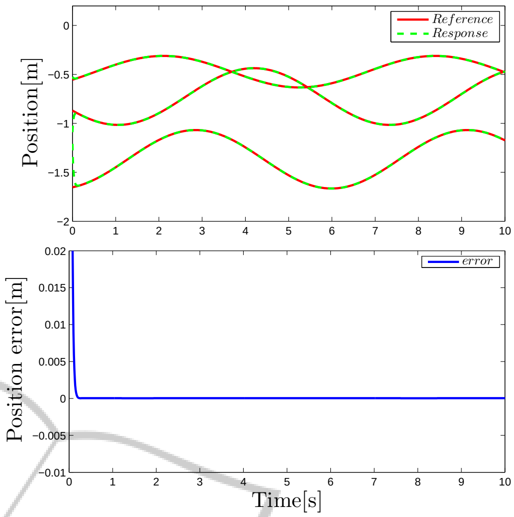

Figure 2: Reference trajectory (solid lines) of the mobile base movement and response(dashed lines) in the task of the virtual robot, with position error.

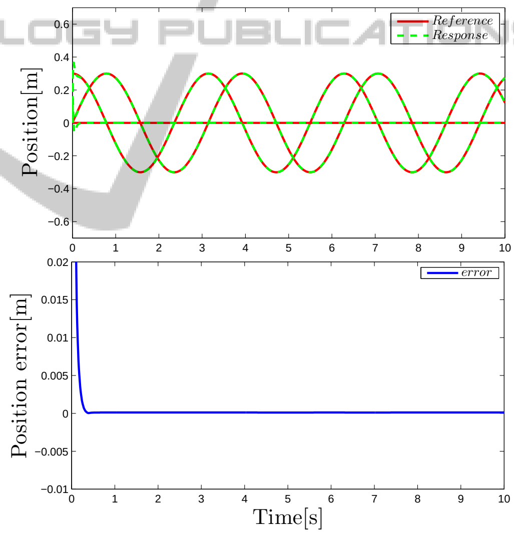

Figure 3: Reference trajectories (solid lines) and responses (dashed lines) for the virtual mechanism task-space position control in the task of winding the wool, with position error.

5 EXPERIMENTAL RESULTS

Experimental setup shown in Fig. 5 and Fig. 8 consists of two 7 DOF Kuka LWR robot arms controlled via Fast Research Interface (FRI). The experiments were performed using the joint stiffness control mode (Schreiber et al., 2010). The dynamic decoupling in Kuka control unit (KRC) allowed us to use a simple velocity control given by Eq. (28) where the weighting matrix was $\boldsymbol{W} = \boldsymbol{I}$.

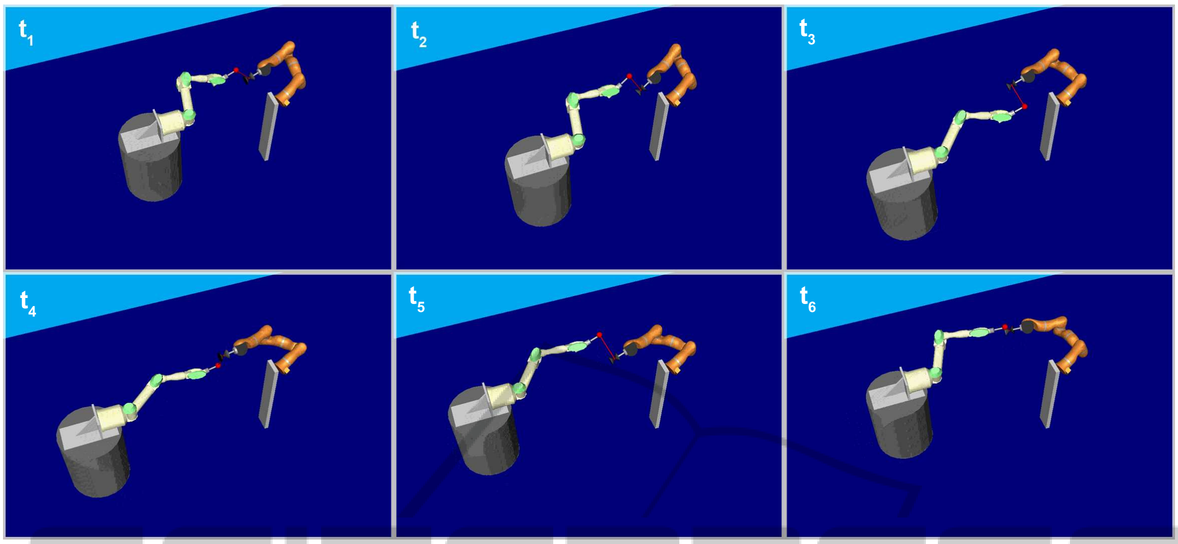

Figure 4: Simulation: winding the wool on a spool with a Kuka LWR arm and PA10 robot on a moving mobile robot Nomad, 6 consecutive instances.

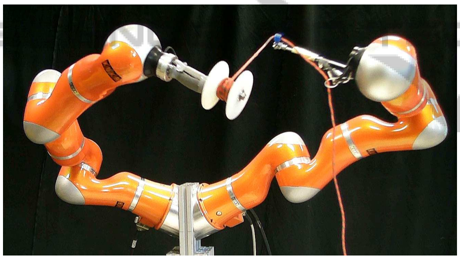

Figure 5: Experimental setup with two Kuka LWR robot arms for task of winding wool on a spool.

5.1 Experiment 1: Winding the Wool on a Spool with the Dual-arm Kuka LWR Robot

While performing the task of winding wool on a spool, the first robot was pushed by a human. This caused the increased torque in joints. When the torque was above threshold value, the robot instantly became compliant. After the perturbation, stiffness become gradually high again.

This gradual change of the stiffness prevented the movements of the robot. The impact of the perturbation can be seen in Fig. 6.

5.2 Experiment 2: Cooperative Holding of More Objects

The task of holding more objects together is a good experiment to show the accuracy of the proposed algorithm. The virtual mechanism task space was defined with three translational coordinates in the frame

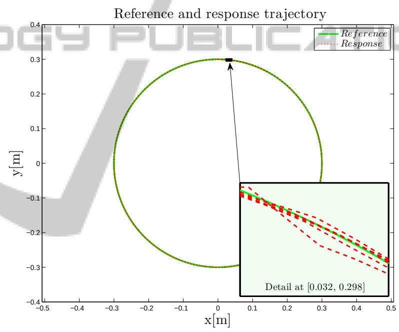

Figure 6: Reference trajectories (solid lines) and responses (dashed lines) for the virtual mechanism task-space position control. The detail show the effect of perturbations on the trajectory.

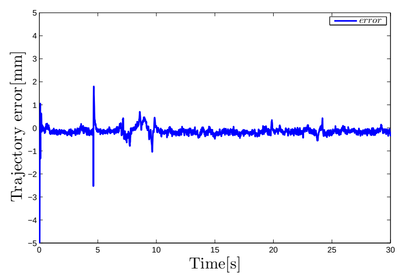

Figure 7: Trajectory error between the reference and response trajectory in the task of winding the wool.

$\mathbf{T}_0$ and a linear movement along z-axis was applied when grasping and dropping a group of seven objects. No force control was used. After grasping the objects together, some velocity perturbations were applied on first four joints of the right robot arm to show the accuracy of the grasp (objects should stay together). Ex-

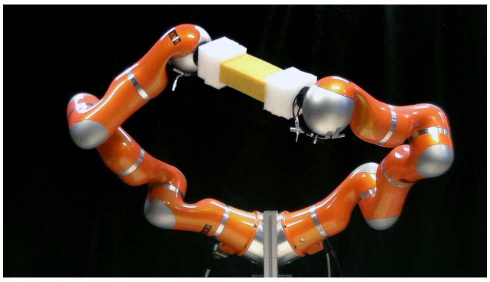

Figure 8: Experimental setup with two Kuka LWR robot arms for task of holding of separate objects together.

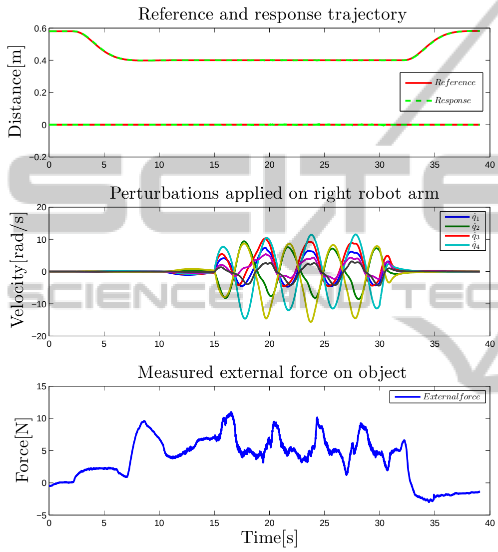

Figure 9: *Top*: reference end response trajectories for grasping and releasing the objects. *Middle*: the velocity perturbations applied on first four joints of right robot arm. *Bottom*: the calculated external force applied on objects, obtained from measurements at end-effector.

perimental results from the experiment are shown in Fig. 9.

6 CONCLUSIONS

In this paper, we proposed a new control strategy for cooperative manipulation. Our approach stated that two robot arms holding the object, form a new augmented kinematic chain. Object is presented as a virtual mechanism with an arbitrary number of degrees of freedom. Therefore, manipulating the object is accomplished by controlling the virtual mechanism.

Our algorithm also cope with the systems, where one of cooperative manipulators base is moving. This type of setup is very common in industry, where one of the robots is mounted on a moving conveyor or mobile robot, as shown in simulation.

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