A Cooperative Robotic System for Handling a Geometrically Unknown Object for Non-Rigid Contact without Force Sensors

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Abstract— This paper presents a new approach to control a cooperative tele-robotic system consisting three slave robots for grasping and handling of an object with unknown geometry and center of mass. A phantom Omni desktop robot is used as a master robot. The contact points between slave robots and the grasped object are non-rigid. It means that rotation in contact points is permitted. Slave robots and the grasped object form a closed kinematic chain with non-actuated joints. This paper proposes a new approach to control the system coping with the non-actuated joints. The dynamic equations of cooperative system are transformed from the joint space into the object space. The slaves dynamic passively decomposed into a locked and a shaped system. The locked system and the shaped system are controlled by two PD controllers. Simulation results show that the position of the slave system that is modeled in Matlab, converges to the position of the real Phantom Omni given by an operator.

I. INTRODUCTION

Cooperative telerobotic system is a good solution when a wide range of objects with different shapes and geometry have to be manipulated. This avoids the use of different grippers for each special object. Moreover, cooperative robotic system has other advantages over single-robot such as improved handling capability and increased loading capacity. However, handling a geometrically unknown object by a cooperative telerobotic system, lead to some kinematic uncertainty in the slave control system.

Most of the research in the kinematic uncertainty of the robotic systems, are dealt with the set point control of position of the object [1], [2], [3]. Cheah et. al. developed trajectory tracking control of a robotic system with kinematic uncertainty. This approach is to control only a single n-DOF robotic manipulator, with kinematic and dynamic uncertainty (e.g., unknown length and weight/inertia for the links, respectively). Position of the tip of the object connected to the robot is measured by transitional position sensor in the task space. This approach cannot be extended to cooperative systems. [4], [5]. Since the Object’s Center of Mass (OCM) could not be measured by position sensor.

Cooperative handling of an object through three robots has been recently investigated by Lee et. al. [6], [7], in which cylindrical and known shape for the object has been assumed. Prabhakar et.al. [8] considered a cooperative system consisting of two robots that rigidly grasp an unknown object. The position and orientation of the object can be completely specified from the position and orientation of either of the manipulators. This approach is not a general approach because the rigid grasp assumption is far from real. Moreover the robots need higher DOF to manipulate the object.

A decentralized adaptive coordinated control method without a force sensor for multiple robot arms grasping a common object is proposed in [9]. The cases of rigid contact and rolling contact are analyzed. However, it is assumed that the OCM is measurable.

A new approach has been recently developed for handling an object of unknown geometry, based on the estimation of center of mass of the object [10], where the object only moves transitionally.

Sirouspour [11] developed a multi-master multi-slave cooperative telerobotic system in which the slave robots cooperatively manipulate a known tool to perform a task on an environment.

In this research, it is assumed that the object has unknown geometry and OCM. It also assumed that the object moves both transitionally and rotationally.

As shown in Fig. 1 the object is considered as a triangle that is obtained by connecting the contact points to each other, once the contact points are confirmed by the human operator. The shaped system controller controls the relative distance of the end effectors and the objective of the locked system controller is to control the position of point $o$ and orientation of the normal vector $r_n$ as shown in Fig. 1.

The master robot is shown in Fig. 2. This robot has 6 degrees of freedom. Therefore, the human operator could control the position of point $o$ and the orientation of the normal vector $r_n$ using the master robot. Where point $o$ is the center of geometry of the contact points.

II. MODELING OF COOPERATIVE TELEROBOTIC SYSTEM

As mentioned before, the cooperative system consists of three nDOF slave robots. The dynamic equation of each slave robot with respect to a common inertial frame is given by the following equation [9].

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i = \tau_i + \sum_{j=1}^{n}j_i^T(q)F_i$$

(1)

where $q_i \in \mathbb{R}^n$ is the generalized coordinate vector of each robot, $M_i(q_i) \in \mathbb{R}^{nxn}$ is the positive definite inertia matrix of the $i^{th}$ robot. $\tau_i \in \mathbb{R}^n$ and $F_i \in \mathbb{R}^n$ are the control generalized force to be designed and external force, respectively. $j_i^T(q)\in\mathbb{R}^{nxn}$ is the Jacobian matrix from joint space to task.
space.

Several important properties of the dynamic equation described by (1) are given as follows [12]:

**Property 1:** The inertia matrix $\mathbf{M}_i(q_i)$ is symmetric and uniformly positive definite for all $q_i \in \mathbb{R}^n$.

**Property 2:** The matrix $\dot{\mathbf{M}}_i - 2\mathbf{C}_i$ is skew-symmetric so that $\mathbf{q}_i^T(\dot{\mathbf{M}}_i - 2\mathbf{C}_i)\mathbf{q}_i = 0$ for all $q_i, q_i \in \mathbb{R}^n$.

The dynamic equations of joint space should be transformed to the object space dynamic equations, then the control of the grasping and handling of the object could be performed independently.

Considering that the position of the end effectors are available, the contact is non-rigid and rotation is possible in contact points, The following variable transformation is proposed to decompose and control the system:

$$
\begin{bmatrix}
\dot{x}_1 \\
\dot{y}_1 \\
\dot{z}_1 \\
\dot{r}_{nx} \\
\dot{r}_{ny} \\
\dot{r}_{nz}
\end{bmatrix}
= 
\begin{bmatrix}
\frac{\dot{x}_1 + \dot{x}_2 + \dot{x}_3}{3} \\
\frac{\dot{y}_1 + \dot{y}_2 + \dot{y}_3}{3} \\
\frac{\dot{z}_1 + \dot{z}_2 + \dot{z}_3}{3} \\
\end{bmatrix}
$$

(2)

where $\mathbf{X}_I$ is the locked system coordinate vector and $\mathbf{X}_E$ is the shaped system coordinate vector, $x_i, y_i$, and $z_i$ are the position of end effector of the $i^{th}$ robot in task space and $\dot{r}_{nx}$, $\dot{r}_{ny}$ and $\dot{r}_{nz}$ are the components of the vector $\dot{r}_n$ that is normal to the plane that crosses through the three contact points. $l_{ij}$ is the distance between the contact point $i$ and contact point $j$ that could be obtained by:

$$
l_{ij} = k \times \sqrt{(x_i(t_0) - x_j(t_0))^2 + (y_i(t_0) - y_j(t_0))^2 + (z_i(t_0) - z_j(t_0))^2}
$$

(4)

Where $t_0$ is the time when the operator confirms that the grasping is completed. $k \leq 1$ is a constant that could be used to adjust the internal grasping force. For example, when the object is flexible one could use a percentage of the $l_{ij}$, for example 90% of the $l_{ij}$ ($k = 0.9$), to make sure that the grasping is stable. Also:

$$
\begin{align*}
\dot{x}_1 &= \frac{\dot{x}_1 + \dot{x}_2 + \dot{x}_3}{3} \\
\dot{y}_1 &= \frac{\dot{y}_1 + \dot{y}_2 + \dot{y}_3}{3} \\
\dot{z}_1 &= \frac{\dot{z}_1 + \dot{z}_2 + \dot{z}_3}{3}
\end{align*}
$$

(5)

The equation of the normal vector is:

$$
\mathbf{r}_n = r_{nx}\mathbf{i} + r_{ny}\mathbf{j} + r_{nz}\mathbf{k}
$$

(6)

Knowing the coordinate of the contact points, $\mathbf{r}_n$ is obtained as:

$$
\begin{align*}
\mathbf{r}_n &= (y_3 - y_1) \times (z_2 - z_1) - (z_3 - z_1)(y_2 - y_1) + [(x_3 - x_1)(y_2 - y_1) - (y_3 - y_1)(x_2 - x_1)]
\end{align*}
$$

(7)

Then

$$
\begin{align*}
r_{nx} &= (y_3 - y_1) \times (z_2 - z_1) - (z_3 - z_1)(y_2 - y_1) \\
r_{ny} &= (z_3 - z_1)(x_2 - x_1) - (x_3 - x_1)(z_2 - z_1) \\
r_{nz} &= (x_3 - x_1)(y_2 - y_1) - (y_3 - y_1)(x_2 - x_1)
\end{align*}
$$

(8) (9) (10)

To control the orientation of the object it is necessary to control the components of normal vector. $\mathbf{X}_I$ and $\mathbf{X}_E$ could be rearranged as:

$$
\begin{bmatrix}
\dot{x}_1 \\
\dot{y}_1 \\
\dot{z}_1 \\
\dot{x}_2 \\
\dot{y}_2 \\
\dot{z}_2 \\
\end{bmatrix}
= 
\begin{bmatrix}
1/3 & 0 & 0 & 1/3 & 0 & 0 \\
0 & 1/3 & 0 & 1/3 & 0 & 0 \\
0 & 0 & 1/3 & 0 & 0 & 1/3 \\
0 & \Delta x_{32} & \Delta y_{32} & \Delta z_{31} & -\Delta y_{31} & 0 \\
-\Delta y_{32} & 0 & -\Delta z_{32} & 0 & \Delta x_{31} & \Delta y_{31} \\
-\Delta y_{32} & \Delta x_{32} & 0 & \Delta y_{31} & -\Delta x_{31} & \Delta z_{31}
\end{bmatrix}
\begin{bmatrix}
x_1 \\
y_1 \\
z_1 \\
x_2 \\
y_2 \\
z_2
\end{bmatrix}
$$

(11)
\[
X_E = \begin{bmatrix}
-2\Delta x_{21} & -2\Delta y_{21} & -2\Delta z_{21} & 2\Delta x_{21} & 2\Delta y_{21} & 2\Delta z_{21} & 0 & 0 & 0 \\
-2\Delta x_{31} & -2\Delta y_{31} & -2\Delta z_{31} & 0 & 0 & 0 & 2\Delta x_{31} & 2\Delta y_{31} & 2\Delta z_{31} \\
0 & 0 & 0 & -2\Delta x_{32} & -2\Delta y_{32} & -2\Delta z_{32} & 2\Delta x_{32} & 2\Delta y_{32} & 2\Delta z_{32}
\end{bmatrix}
\]

using (11) and (12) decomposition matrix is defined as:

\[
\begin{bmatrix}
\dot{X}_l \\
\dot{X}_E
\end{bmatrix} = S(q)X
\]

where \(X=[x_1 \ y_1 \ z_1 \ x_2 \ y_2 \ z_2 \ x_3 \ y_3 \ z_3]^T\), and \(S\) is obtained easily as:

\[
S(q) =
\begin{bmatrix}
1/3 & 0 & 0 & 1/3 & 0 & 0 & 1/3 & 0 & 0 \\
0 & 1/3 & 0 & 0 & 1/3 & 0 & 0 & 1/3 & 0 \\
0 & 0 & 1/3 & 0 & 0 & 1/3 & 0 & 0 & 1/3 \\
\Delta x_{32} & 0 & -\Delta y_{32} & 0 & \Delta z_{32} & -\Delta y_{31} & 0 & -\Delta x_{31} & -\Delta z_{31} \\
-\Delta y_{32} & \Delta x_{32} & 0 & -\Delta y_{31} & 0 & \Delta x_{31} & 0 & \Delta z_{31} & 0 \\
2\Delta x_{21} & 2\Delta y_{21} & 2\Delta z_{21} & 0 & -2\Delta x_{21} & -2\Delta y_{21} & -2\Delta z_{21} & 0 & 0 \\
2\Delta x_{31} & 2\Delta y_{31} & 2\Delta z_{31} & 0 & 0 & 0 & 2\Delta x_{32} & 2\Delta y_{32} & 2\Delta z_{32}
\end{bmatrix}
\]

To transform the dynamic equations of joint space into object space the following transfer matrix could be used:

\[
T = S \cdot J
\]

where \(J\) and \(S\) are transformation matrices from the joint space into task space and from task space into object space, respectively.

\[
J = \begin{bmatrix}
I_1 & 0 & 0 \\
0 & I_2 & 0 \\
0 & 0 & I_3
\end{bmatrix}
\]

Where \(I_i\) is the Jacobian matrix of the \(i^{th}\) robot. Using the transfer matrix \(T\), the dynamic equations in the object space could be obtained as:

\[
M_L(X)\dot{X}_L + C_L(X, \dot{X})\dot{X}_L + C_{LE}(X, \dot{X})\dot{X}_E = T_L + F_L
\]

\[
M_E(X)\dot{X}_E + C_E(X, \dot{X})\dot{X}_E + C_{EL}(X, \dot{X})\dot{X}_L = T_E + F_E
\]

(17) and (18) are the equations of the locked and shaped systems in the object space, respectively. These equations are decomposed passively such that each of the decoupled systems could be controlled independently.

In (17) and (18):
where $X_i = [x_i, y_i, z_i]^T$ is the task space coordinates vector for $i^{th}$ robot.

\[
\begin{bmatrix}
T_L \\
T_E
\end{bmatrix} = T^{-T} \begin{bmatrix}
\tau_1 \\
\tau_2 \\
\tau_3
\end{bmatrix}, \quad \dot{X}_i = J_i(q_i)\dot{q}_i, \quad X = \begin{bmatrix}
X_1 \\
X_2 \\
X_3
\end{bmatrix}
\tag{19}
\]

Decoupling terms, i.e. $C_{LE}(X, \dot{X})X_E$ and $C_{EL}(X, \dot{X})X_L$, are obtained as follows:

\[
\begin{bmatrix}
C_L \\
C_{EL} \\
C_E
\end{bmatrix} = T^{-T}(C_i(q_i, \dot{q}_i) - M_i(q_i)T^{-T}T) \times T^{-1}
\tag{22}
\]

III. COOPERATIVE SYSTEM'S CONTROLLER DESIGN

Assuming that there is no time delay and the telerobotic system is unilateral. The communication channel is passive.

Then the controller of the slave system could be controlled independently. In this section, two controllers, $T_E$ and $T_L$ (i.e. control actions for the locked and shaped subsystems of the slave system, respectively) are designed in object space as follows:

\[
\begin{bmatrix}
T_L \\
T_E
\end{bmatrix} = \begin{bmatrix}
C_{LE}(X, \dot{X})X_E \\
C_{EL}(X, \dot{X})X_L
\end{bmatrix} + \begin{bmatrix}
U_L \\
U_E
\end{bmatrix}
\tag{23}
\]

It is shown in [6] that $C_{LE} = -C_{EL}$ and $\dot{X}_i^T C_{LE}(X, \dot{X})X_E + \dot{X}_i^T C_{EL}(X, \dot{X})X_L = 0$, hence the decoupling procedure does not generate (or dissipate) any mechanical power.

The telerobotic system is unilateral with no time delay in communication channel then the teleoperation will not cause any instability in the cooperative telerobotic system.

Given the decoupling control (23), the shaped and the locked system dynamics can be expressed as:

\[
M_E(X)\ddot{X}_E + C_E(X, \dot{X})\dot{X}_E = U_E + F_E
\tag{24}
\]

\[
M_L(X)\ddot{X}_L + C_L(X, \dot{X})\dot{X}_L = U_L + F_L
\tag{25}
\]

where the gains $K_E^p$ and $K_E^b$ are symmetric positive definite matrices. The effect of external force, $F_E$, would be compensated by adjusting the proportional gain $K_E^p$ in (25) [7]. The control law for the locked system is considered as:

\[
U_L = -K_L^p e_L - K_L^b e_L
\tag{26}
\]

where the gains $K_L^p$ and $K_L^b$ are symmetric positive definite matrices. $e_L = X_L - X_L^d$ is the position error of the locked system. The desired trajectory for the locked system is given by the Phantom Omni robot that is used as the master robot and is being manipulated by the human operator.

IV. SIMULATION AND SEMI-EXPERIMENTAL RESULTS

In this section, the control systems developed in previous sections are evaluated by simulations performed in Matlab/Simulink environment using SimMechanics toolbox. The slave robots considered in this work are 3 DOF Cartesian robots.

This robot has simple dynamics; its Jacobian matrix is identity. It is also assumed that contact points between
finger ends and object surface are non-rigid, i.e. the rotation between fingers and the object's surface are permitted. A schematic of the considered robot is shown in Fig. 3.

As shown in Fig. 4, the object is modeled by three links using SimMechanics toolbox. Each link is connected to its corresponding robot. In Fig. 4, one degree of freedom for each robot is shown with a triangle.

The links are modeled with Body Block and connected to each other by Weld Joint. The Cartesian degrees of freedom, x, y and z of each robot are modeled by Prismatic Joints. Contact between robots and object is considered as 3DOF joint. These joints are modeled by Gimbal Joint blocks in SimMechanics. Position of the contact points are measured in SimMechanics by Body sensors.

The object’s mass is assumed to be 3kg \((m_1 + m_2 + m_3 = 3 kg)\) and its center of mass is located in point \(G\) as shown in Fig. 4.

The desired trajectory of the locked system is defined as:

\[
X_t^d = [-\sin(t) \cos(t) - \cos(t) \sin(t)]^T
\]

\[
dX_t^d = [-\cos(t) + 1 - \sin(t) \sin(t) \cos(a^d)]^T
\]

where \(a^d, \beta^d, \) and \(\gamma^d\) the desired angles of the normal vector with respect to x, y and z axes, respectively.

Fig. 5 shows the Circular trajectory tracking of the locked system. As it is shown in the Fig. 6 the trajectory tracking error of the locked system converges to zero in 5 seconds. Fig. 7 shows the orientation error of the locked system. As shown in Fig. 7 the orientation error converges to zero very fast.

For semi-experimental, a Phantom Omni haptic devise is used as a master robot which is connected to Matlab via 1394 serial port protocol. An operator manipulating the master robot gives desired trajectory.

Figures 8, 9 and 10 show the trajectory tracking of the virtual object in response to the trajectory given by actual operator. The semi-experimental results show that the trajectory tracking error is bounded and acceptable for the proposed control system. As shown in the Fig. 10 the error in z direction is higher than errors of x and y directions. This is due to the fact that gravity is not compensated and the controller is not a model-base controller.

V. CONCLUSION

A cooperative telerobotic system is developed for grasping and handling an object with unknown geometry using a Phantom Omni as the master robot. The slave system consists of three Cartesian robots that cooperatively handle the object. The geometrically unknown object is modeled by three links. The dynamic equations of slave system are passively decomposed into two separate dynamics, i.e. shaped and locked dynamics. Two PD controllers are developed for the shaped and locked...
systems. Simulation results show good trajectory tracking for the locked system. The semi-experimental results show that the trajectory tracking error is bounded and acceptable for the proposed control system.

REFERENCES


