Mapping of Human Hand Motion to Robotic Gripper for Telemanipulation Tasks

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1. Abstract:

This work focuses on mapping human hands jestures into robotic hand postures of similar and lower dimension, for teleoperation tasks. The research mainly focuses on robotic hands of 3 and 5 fingers, both from the aspect of mimicking the operator movement and from aspect of feeding the user with relevant feedback regarding contacts during the manipulation tasks. A semi point-to-point semi position mapping algorithm is applied for the position mapping. For the force mapping, an algorithm based on the robotic hand jacobian is applied. We than show a test including grasping and manipulation of common household tools and objects, based on real-time motion mimicking of the operator's hand, in a real experimental setup.

Keywords: Robotic Hands, Teleoperation, Telemanipulation, Grasp planning, Haptics

2. Introduction:

In a teleoperation scenario, tasks are performed by a mechanical manipulator controlled remotely by a human operator provided with force reflecting haptic interface, thus enabling interaction with the remote environment (1). One of the main challenges is dexterous manipulation of various remote objects, also called Telemanipulation. Among the different applications for that one can see the remote surgical robots, such as the DaVinci robot, and the Talon robot which is used for bomb disposal (2). This ability is achieved using force feedback, provided usually by the end effectors' sensors. Achieving an exact manipulation of delicate objects using 5-finger grippers is very difficult (due to complexity induced by high number of d.o.f). For that reason, gripping tasks for industrial purposes are done using 2 to 3 finger grippers. This provides us with 2 challenges:

1) Mapping the operator's hand motion which is usually used to control the slave robot's end effector, to 3 finger gripper motion.

2) Mapping the human hand motion to 5-finger gripper motion for exact manipulation tasks (3; 1; 4).

Our research focuses on formulation of a mapping algorithm – used to transform hand motion, gathered by data acquisition glove to 3 and 5 finger robotic gripper's motion and deliver back force feedback. The mapping algorithm procedure includes:

- Formulation of the human hand and robotic gripper's kinematics.
- Formulation of position control law, used to map the human hand motion to gripper motion.
- Formulation of force-feedback control law, used to map the force-torque measurements, Gathered from the grippers fingers to the operator's hand.

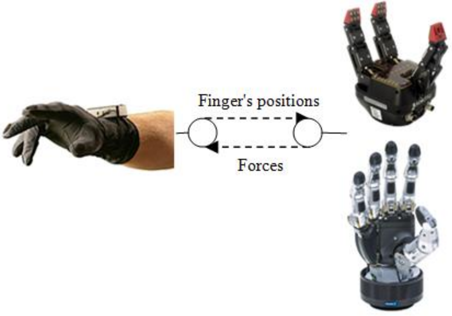

Figure 1 - Human/Robot connection

We than show an experimental setup, used to evaluate the gripper's ability to grasp different object (based on the grasp taxonomy of Cutkosky (5)), and compare between the 2 grippers according to the taxonomy.

I. PROBLEM FORMULATION

In order to perform complex manipulation tasks remotely, the development of an intuitive Telemanipulation system is needed. The development process must consider the following parameters:

- The ability to operate the system from a distance – distant operation must take into consideration the latency, introduced by network communication and delay which can be caused from the different system's ingredients.
- Intuitive grasping – mimicking operator's motion and sending back feedback which reflect interaction with the remote environment surroundings.
- Ability to manipulate and operate a variety of objects/tools.

- Hand and Gripper's Kinematics – existence of kinematic structure difference leads to the conclusions that intuitive grasping can be achieved only by mapping based on position algorithm for mimicking motion and force-feedback mapping for sending back feedback.

Position Algorithm Formulation:

The algorithms used so far for mapping human hand motion to robotic gripper's motions were (3; 6):

1) Fingertip algorithm (point-to-point mapping) – the position of each particular position in the finger is replicated to the mechanical finger. It has the advantage of being more accurate than other algorithms and defining the mechanical hand position more precisely. The disadvantage is that one must solve the inverse kinematics of the mechanical hand for that, which is sometimes time consuming.

2) Joint-to-joint mapping – each joint of the data glove (or any other manipulation device) is directly associated with a joint of the robotic hand. It's main advantage is that it's very simple to implement. While it's main disadvantage is that differences in relative position of the human fingers can cause problems in the robotic hand due to kinematic differences.

3) Pose Mapping algorithm – a particular pose of the human hand is associated with a predefined pose of the robotic hand. While this algorithm has the advantage of being able to program the robotic hand pose. The disadvantage is that each pose of the human hand has to be properly defined and the robotic hand posture must be properly chosen.

4) Synergy based algorithm – this algorithm depends on the existence of general lines of movement (6), each one of them is tranfered to the robotic hand in order to create similar grasp. It's advantage is that the robotic hand poses which are created here, produce much efficient grasp in terms of force/form closure. One of it's disadvantages is that it's less intuitive to the human operator who sends the initial gesture because it's not neccesarily mimicks the hand pose.

The algorithm used in our research is a combination of a Fingertip and Pose Mapping algorithms. This algorithm requires first the hand and gripper's kinematic formulation.

Force-Feedback Algorithm Formulation:

The force-feedback is achieved using force constraints. Force constraints are usually achieved by using virtual springs or saturations on the max allowed force at the moment of contact. The force-feedback depends also on the force measurements in the robotic systems. That can be achieved using force sensors or tactile sensors (7; 8). In our research the last one was used for measurements and data transfer.

II. HAND AND GRIPPER'S KINEMATIC FORMULATION

Shown in the section is the robotic and human hand kinematics, achieved using D.H (Denavit-Hartenberg) parameters (human hand kinematics is also shown in, (1). 3 finger gripper kinematics is also shown in (9; 1), 5 finger gripper kinematics is computed based on (10)), shown here is kinematic formulation of one of the fingers in each one of the robotic and human hands.

In this research, we used two types of grippers: Robotiq 3 Finger[1] and Schunk SVH5 Hand[2]. The formulation for the 1st finger for the Robotiq 3 Finger Adaptive Gripper:

(1)

$$ {}^{0}A_{F_{1T}} = \begin{bmatrix} C_{qF11+qF12+qF13} & S_{qF11+qF12+qF13} & 0 & l_0 + l_1 C_{qF11} + l_2 C_{qF11+qF12} + l_3 C_{qF11+qF12+qF13} \\ -S_{qF11+qF12+qF13} & C_{qF11+qF12+qF13} & 0 & -l_1 S_{qF11} - l_2 S_{qF11+qF12} - l_3 S_{qF11+qF12+qF13} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

For the Schunk SVH5 Hand, the formulation for the 1st finger:

(2)

$$ {}^{0}A_{F_{1T}} = \begin{bmatrix} c_{qF12+qF13+qF14} c_{qF11} & -s_{qF12+qF13+qF14} c_{qF11} & s_{qF11} & V + Ac_{qF11} c_{qF12} + Bc_{qF11} c_{qF12+qF13} + Cc_{qF11} c_{qF12+qF13+qF14} \\ c_{qF12+qF13+qF14} s_{qF11} & -s_{qF12+qF13+qF14} s_{qF11} & c_{qF11} & s_{qF11} \left(Bc_{qF12+qF13} + Ac_{qF12} + Cc_{qF12+qF13+qF14} \right) \\ s_{qF12+qF13+qF14} & c_{qF12+qF13+qF14} & 0 & Z + Bs_{qF12+qF13} + Y tan(X) + As_{qF12} + Cs_{qF12+qF13+qF14} \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

In order to simulate the algorithm before experimental implementation, one must simulate also the human hand. For the human hand, the transformation matrix for the 1st finger (thumb) is:

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[1] http://robotiq.com

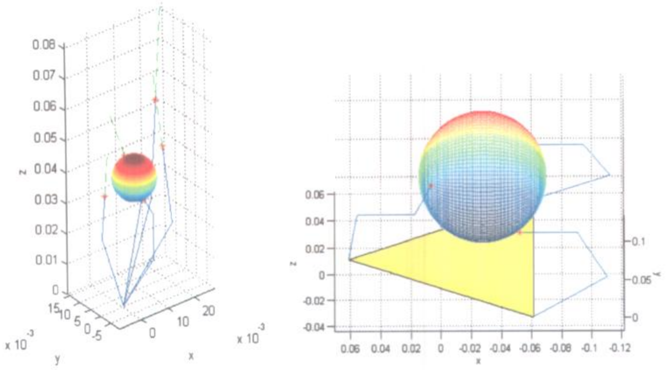
[2] https://schunk.com

$$(3)\quad {}^{0}A_{h_{tT}} = \begin{bmatrix} c_{q12+q13+q14} * C_{q11} & -s_{q12+q13+q14} * C_{q11} & -S_{q11} & C_{q11}\left(a_{13}C_{q12+q13} + a_{12}C_{q12} + a_{14}C_{q12+q13+q14}\right) \\ c_{q12+q13+q14} * S_{q11} & -s_{q12+q13+q14} * S_{q11} & C_{q11} & S_{q11}\left(a_{13}C_{q12+q13} + a_{12}c_{q12} + a_{14}c_{q12+q13+q14}\right) \\ -s_{q12+q13+q14} & -c_{q12+q13+q14} & 1 & -a_{13}S_{q12+q13} - a_{12}S_{q12} - a_{14}S_{q12+q13+q14} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

III. POSITION CONTROL LAW FORMULATION

The position control law is based on position mapping of the human hand gestures to robotic gripper's movements. The position mapping algorithm used here is consisted of the following steps:

1. Using kinematic formulation of the hand to reflect points of contact. By using forward kinematics on the hand transformation matrices, a minimal contact sphere can be constructed (also seen in (6)).Shown in Figure **2**a is an example of the algorithm for the 3 finger gripper.



(a) (b)

Figure 2– a – Minimal Sphere for Position Mapping, b – 3 Finger contact sphere

Once human hand fingers contact sphere is calculated, followed by computation of minimal distance between fingers, two scaling factors are calculated. The first scaling factor is calculated between human thumb and gripper thumb. The second scaling factor is calculated between the second and third human fingers (which were used to construct the contact sphere) and the second and third fingers in the gripper. Using these scaling factors, the following contact sphere is transformed to another contact sphere, which is used by the gripper as shown in (b)
Figure **2**b.

2. Fingertip position is than mapped into gripper's joint angles using inverse kinematics
3. Joint motor angles are than computed from gripper joint angles using the following relation:

$$(4)\quad A\theta_M = q_F$$

While:

$$(5)\quad q_F = [q_{F11} \quad q_{F12} \quad q_{F13} \quad q_{F21} \quad q_{F22} \quad q_{F23} \quad q_{F24} \quad q_{F31} \quad q_{F32} \quad q_{F33} \quad q_{F34}]^T$$

$$(6)\quad \theta_M = [\theta_{M1} \quad \theta_{M2} \quad \theta_{M3} \quad \theta_{M4}]^T$$

The matrix A is computed based on joint motor's angle echo, indicating maximal closure of gripper's fingers. Afterwards one can use A to compute motor's values for a given joint angle as is shown next:

$$(7)\quad \theta_M = [204 \quad 142 \quad 138 \quad 59]^T$$

4. Joint motor angles are than fed back to the gripper, to achieve the gripper's minimal sphere as shown in Figure **2**b.

IV. FORCE-FEEDBACK MAPPING

Detection of contact in the remote environment is necessary in Teleoperation applications, especially in areas where there is a lack of other form of feedback (i.e. visual feedback). This feature is achieved using some form of haptic manipulation device and force or tactile sensors on the robotic system. In this research a TakkTile sensors has been used to detect contact and measure the force required to manipulate the remote object (without damaging it). These sensors were attached to the robotic hands. Force measurements were then transferred to the manipulation device (data glove in our system) in the form of different levels of vibration forces as can be seen in Figure 3 for the Robotiq Gripper.

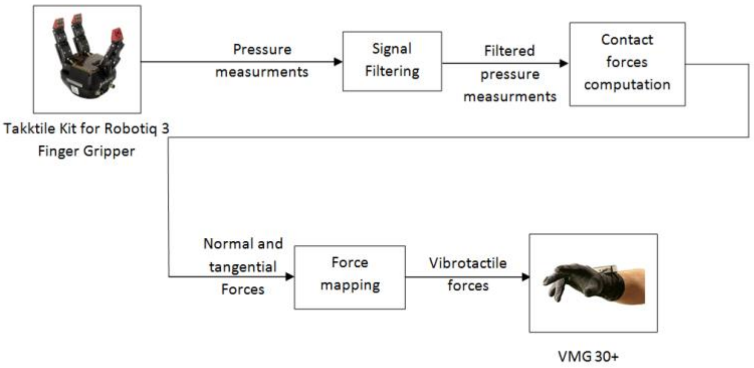


Figure 3 - Force-Feedback Mapping for the Robotiq Gripper

Similar system can be seen in (1). The problem formulation is stated next.

V. FORCE-FEEDBACK PROBLEM FORMULATION

In order to guarantee a grip on an object without damaging it, force-feedback is necessary. This form of feedback is derived from forces measurements, based on the following relations:

$$(8)\quad F_q = \begin{bmatrix} \sum_1^k f_k \frac{\partial r_k}{\partial q_1} \\ \sum_1^k f_k \frac{\partial r_k}{\partial q_2} \\ \vdots \\ \sum_1^k f_k \frac{\partial r_k}{\partial q_n} \end{bmatrix} = J_c{}^T \mathrm{F_e}$$

Fe is a vector containing torques acting on the gripper's fingers.

$$(9)\quad F_e = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{bmatrix}$$

At the moment of contact, the constrained LaGrange equations are:

$$(10)\, M(q)\ddot{q} + B(q,\dot{q}) + G(q) = F_q + W^T\lambda = F_q + \left(\frac{\partial h}{\partial q}\right)^T \lambda$$

Where:

$$(11)\, h(q) = r_p - P = 0$$

r_p is the translation vector of each finger and P is the end point of each fingertip. If impact isn't encountered during contact and contact is maintained, it is safe to assume that rigid bodies' velocity and acceleration are negligible

$$\dot{q} \approx \ddot{q} \approx 0$$

So eq. (10) becomes:

$$(12)\, G(q) = F_q + W^T\lambda \rightarrow F_q = G(q) - W^T\lambda$$

While

$$(13)\, G(q) = \frac{\partial V_g}{\partial q_i}, V_g = \sum_{j=1}^{3} -m_i r_i \cdot g$$

V_g is the finger's potential energy, created during grasp. Constraint forces vector λ, created during contact, is measured using the Takktile sensors (as can be seen in Figure 4 for the 3 finger gripper) and contains two tangential and one normal components, as can be seen in eq. (14).

$$(14)\, \lambda = \begin{bmatrix} \lambda_n \\ \lambda_{t1} \\ \lambda_{t2} \end{bmatrix}$$

This vector is converted to vibration forces/torques, applied on the human hand using the data glove based on the following relation:

$$(15)\, F_{hand} = \frac{\partial r_1}{\partial q_1} f_1 + \frac{\partial r_2}{\partial q_1} f_2 + \cdots + \frac{\partial r_n}{\partial q_1} f_n = J_h^T F_h$$

By comparing the generalized forces, we get:

$$(16)\, F_q = F_{hand} \rightarrow J_c^T F_e = J_h^T F_h \rightarrow F_h = J_h^{-T} J_c^T F_e \rightarrow \boxed{F_h = J_h^{-T} F_q}$$

That is the connection between the gripper's measured forces during contact and the vibration forces, felt by the human operator.

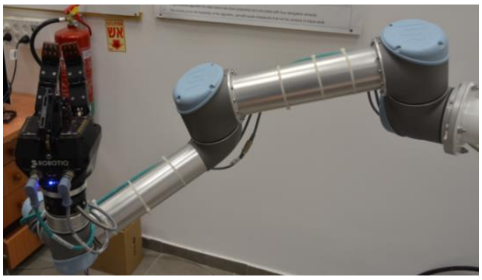


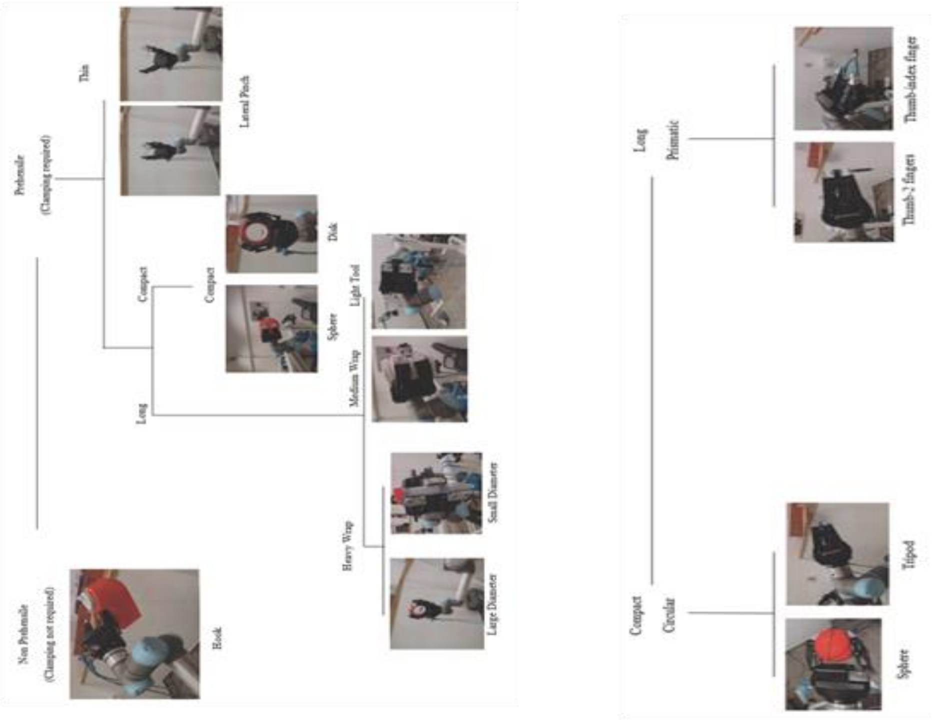
Figure 4 - Takktile sensors on the 3 Finger Gripper

VI. GRASPING TESTS

The proposed Telemanipulation system is compose d.o.f two robotic hands, Robotiq 3-Finger Adaptive Gripper and Schunk SVH-5 Finger Hand. Classification of each one of them to the correct grasping assignments is based on a grasping and manipulation test, shown next.

Grasping and Manipulation Test:

In order to decide which robotic hand is more efficient from the mentioned above robotic hands. Comparison method was revised, based on the Cutkosky grasping test (5). The performance results of the SVH 5-Finger hand which are summarized in (4) were compared to the 3 finger hand performance results, shown in Figure 5a (power grasps) and Figure 5b (precision grasps). The last are based on experiments performed in our lab.



(a) **(b)**

Figure 5 – a – Power Grasps, b – Precision Grasps

3. CONCLUSIONS

Based on the taxonomy proposed by Cutkosky (5), test objects where gathered and tested in our lab, these items were: Disk, ball, large diameter cylinder, tray, small diameter cylinder, pen/pencil, screwdriver, a cutting tool, test tube, large and small tanks. These objects were tested using the Robotiq Gripper, and compared to the results in (4). It was found that both grippers had similar performance results in the power grasps test (the Robotiq Gripper had higher payload capabilities). In the precision grasps, the SVH hand handled more grasps. For missions involving higher dexterity with low weight, the SVH hand was found to be more appropriate. If high weight carriage is required, the Robotiq Gripper is more appropriate. The position mapping method, used in the current research was found to be intuitive for our use in the lab and in performing the grasping test, but more testing is required based on the current grasping test and additional metrics, same goes for our force-feedback mapping.

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