Human-inspired object load transfer in hand-over tasks

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***Abstract*—A human-inspired hand-over control strategy is proposed for the haptic interaction of two dual-fingered hands. It can be applied to robots that are intended to assist older adults and people with motor impairments and it focuses on the timing and synchronization which is required for a successful object load transfer.**

I. Motivation

The natural integration of robots in the human environment and their ability to assist or cooperate with humans is becoming increasingly important. Therefore, the handing over of different kinds of objects is a basic functionality that needs to be mastered in order to achieve a fluent human-robot haptic interaction. One of the main challenges of a hand-over task is the force and energy exchange that occurs during the transferring of the object load. Human studies have shown that during the object transfer, as time increased, the grip and load forces decreased linearly for the giver and increased linearly for the receiver [4, 3, 2]. Hence, the object weight transfer system consists of an object held by the fingers of a giver and a receiver hand, where the latter usually has no knowledge of the object's weight. The stability of the object during this transfer strongly depends on the timing and synchronization of the giver and receiver.

This work focuses on the human-inspired timing and synchronization required by the participants during a hand-over task to ensure a dynamically stable object load transfer. The objective is to form human-inspired strategies that can be evaluated through human-robot hand-overs particularly in cases of robotic assistants to elderly or humans with motor impairments. In these cases, robotic assistants either as receivers or givers of objects should be totally responsible for the successful completion of the hand-over task. Our work focuses on haptic interactions, which we believe play an important role in the accomplishment of fluent hand-overs and it is our assessment that an object weight estimator and a dynamically stable grasper must be the foundations upon which a hand-over strategy is devised. In our work, we exploit a control law that possesses these attributes [1].

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In our previous work [5], the object load transfer strategy is initiated by the giver who linearly decreases its load and grip forces until the full release of the object's load. It is assumed that the receiver estimates the load transfer successfully and adapts its grip forces accordingly to achieve an efficient object transfer. Hence, in case the receiver is not a fully responsive participant and does not or cannot instantly accept the released load, this strategy fails. It can, however, be applied successfully in a hand-over where the receiver is the robotic assistant.

II. Proposed strategy

We propose an object load transfer strategy for cases where the robotic participant is the giver. It is receiver initiated and it involves a rich haptic interaction between the hands. In this strategy, the giver is a stably grasping robotic hand that follows closely the receiver's lead and ensures haptically that the receiver has stably grasped the object before opening its grip. Therefore, the receiver can be anyone from a fully cooperative robot to an insufficiently responsive human.

The proposed strategy for the giver is as follows. It is assumed that the robotic giver has already stably grasped the object and has knowledge of the object's weight via the weight estimator (controller [1]). During the object load transfer, the giver continuously estimates whether the object has been fully transferred to the receiver and adjusts its grip force accordingly so that it always remains within the friction cone. When the weight estimation reaches zero or becomes slightly negative, the object has been handed over to the receiver and the giver releases the object by opening its grip.

In order to study the proposed strategy, we consider a robot-to-robot handover with a simple receiver strategy operating under the same controller as the giver. The receiver comes into an initial contact with the object which is grasped by the giver and initiates the object transfer by linearly increasing its load and grip forces [2]. As it was described in the robotic giver strategy, when the object has been fully transferred the giver opens its grip. The sudden opening of the giver's fingers causes an immediate load change at the receiver which is used as haptic cue for the robotic receiver to switch to the object weight estimator and the grip force adaptation concluding the object load transfer.

A Lyapunov based theoretical analysis performed for the overall system comprised by the object and the two robotic hands shows that the system converges to a new attractive equilibrium (see Appendix).

In case the receiver is a not fully responsive human, he may not be able to carry the full load of the object and the load/grip forces are not necessarily linearly increasing. Nonetheless, the robotic giver according to the proposed strategy ensures the object's safe grasp by successfully estimating the transferred object load as demonstrated in the simulations results.

III. Simulation Results

A simple 2D example is utilized to demonstrate our idea with emphasis on haptic interactions. The simulation is performed for an object with parallel surfaces but can be applied to objects of unknown shape. An object of mass 0.08 kg is considered. At $t_0 = 5.5$ sec, the receiver is just in contact with the object which is already stably grasped by the giver. The object load transfer begins at $t_{start} = 6.5$ sec and lasts 0.5 sec which is based on human studies [2]. During the transfer, the force applied by the object to the giver is decreasing in response to the load taken by the receiver until it crosses zero and reaches a negative value (just after $t = 7$ sec - sub-plot of Fig. 1) when the giver totally releases the object. This is sensed by the receiver from the sudden increase of the velocity of the receiver's fingertips and he subsequently activates, at t_b, the object's weight estimate (Fig. 1). The object load transfer is complete and the receiver stably grasps the object at a final equilibrium position (at approximately $t = 9$ sec).

In order to demonstrate the difference between the proposed strategy and the strategy in [5], we consider an inadequately responsive receiver who takes only a quarter of the object's load 0.02 kg. In the giver initiated strategy [5], the object practically slips from the receiver's fingers since the giver has already released its load (Fig. 2 - dashed line). In the proposed strategy the giver guarantees the object's safe grasp by never releasing the object (Fig. 2 - solid line).

IV. Conclusion

A stable human-to-robot hand-over strategy is proposed for two dual-fingered hands. It accomplishes a natural object load transfer based on human findings and haptic interaction clues. It will be evaluated in the future through human-robot hand-overs implementing different human behaviors since the robotic participant ensures the object's safe grasp even if the human participant is not fully responsive.

Appendix

Brief Description of the Equilibrium and Stability of an Object held by two Dual Fingered Hands

The main phase of the object load transfer is characterized by a system consisting of a receiver hand ($j = 1$) and a giver hand ($j = 2$) in contact with a rigid object of mass m_o with parallel surfaces and width l in the gravity field (Fig. 3). Each hand consists of two fingers ($i = 1, 2$ for the giver, $i = 3, 4$ for the receiver) of 3 degrees of freedom

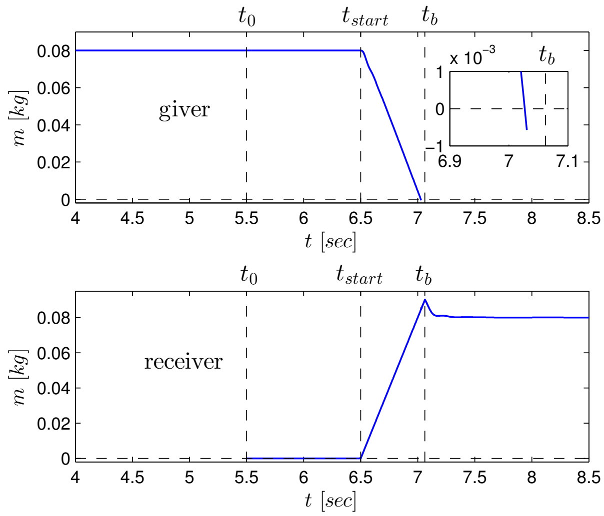

Fig. 1: Object load transfer.

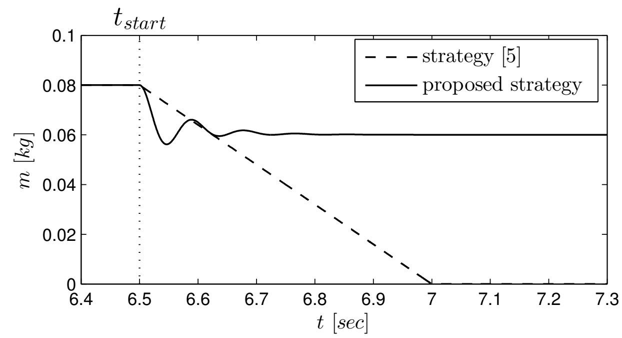

Fig. 2: The giver's object load in case of an insufficiently responsive receiver with the proposed strategy (solid line) and strategy [5] (dashed line).

with revolute joints and rigid hemispherical tips of radius r. Vector $\mathbf{q_i} = \begin{bmatrix} q_{i1} & q_{i2} & q_{i3} \end{bmatrix}^T$ denotes the joint angles for the i_{th} finger ($i = 1, \ldots, 4$). In the following, R_{ab} denotes the rotation matrix of frame $\{b\}$ with respect to frame $\{a\}$ unless the reference frame is the inertia frame $\{P\}$ in which case it is omitted. $R(\theta)$ is a rotation through an angle θ about the z axis that is normal to the x-y plane pointing outwards. Let $\{P\}$ be the inertia frame attached at the base of the first finger and $\{O\}$ be the object frame placed at its center of mass (Fig. 3) and described by the position vector $\mathbf{p_o} \in \mathbb{R}^2$ and the rotation matrix $R_o = R(\theta_o)$. Let $\{t_i\}$ be the i_{th} fingertip frame described by position vector $\mathbf{p_{t_i}} \in \mathbb{R}^2$. Let frame $\{c_i\}$ be attached at the contact point of each finger with the object with its x axis aligned with the normal to the object surface pointing inwards and let ${}^o\mathbf{p_{oc_i}} = [X_i \ Y_i]^T$ be its position on the object frame. Frame $\{c_i\}$ is described by position vector $\mathbf{p_{c_i}} \in \mathbb{R}^2$. Let $\mathbf{n_{c_i}}, \mathbf{t_{c_i}} \in \mathbb{R}^2$ be the normal pointing inwards and the tangential vectors to the object at the contact points, expressed in $\{P\}$, hence $R_{c_i} = [\mathbf{n_{c_i}} \ \mathbf{t_{c_i}}]$. Notice that $\mathbf{p_{c_i}} = \mathbf{p_{t_i}} + r\mathbf{n_{c_i}}$.

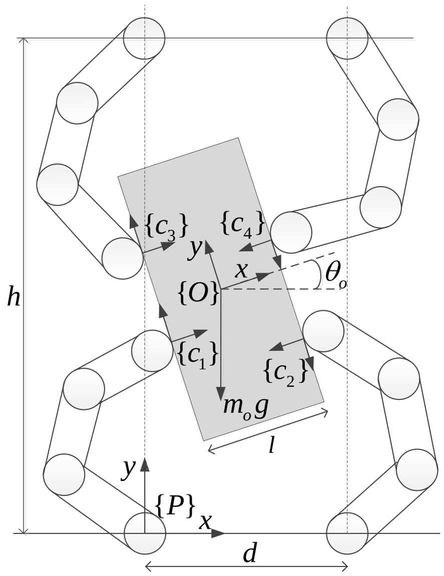

Fig. 3: System of robotic fingers grasping a rigid object with parallel surfaces

We model the system under the following contact and rolling constraints [1]:

$$\begin{bmatrix} D_{ii} & D_{i5} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{q}}_\mathbf{i} \\ \dot{\mathbf{p}}_\mathbf{o} \\ \dot{\theta}_o \end{bmatrix} = 0, \; \begin{bmatrix} A_{ii} & A_{i5} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{q}}_\mathbf{i} \\ \dot{\mathbf{p}}_\mathbf{o} \\ \dot{\theta}_o \end{bmatrix} = 0 \quad (1)$$

where

$$D_{ii} = \mathbf{n_{c_i}}^T J_{v_i}, \qquad D_{i5} = \begin{bmatrix} -\mathbf{n_{c_i}}^T & \mathbf{n_{c_i}}^T \hat{p}_{oc_i} \end{bmatrix} \quad (2)$$

$$A_{ii} = \mathbf{t_{c_i}}^T J_{v_i} + r_i J_{\omega_i}, \qquad A_{i5} = \begin{bmatrix} -\mathbf{t_{c_i}}^T & \mathbf{t_{c_i}}^T \hat{p}_{oc_i} \end{bmatrix} \quad (3)$$

with $\mathbf{p_{oc_i}} = \mathbf{p_{c_i}} - \mathbf{p_o}$ and for a vector $\mathbf{p} = [a \; b]^T$ we define $\hat{\mathbf{p}} = [b \; -a]^T$ so that $\hat{\mathbf{p}}^T \mathbf{k} \; \forall k \in \mathbb{R}^2$ defines the outer product $\mathbf{p} \times \mathbf{k}$. The Jacobian matrices $J_{v_i} = J_{v_i}(\mathbf{q_i}) \in \mathbb{R}^{2\times 3}$, $J_{\omega_i} = J_{\omega_i}(\mathbf{q_i}) \in \mathbb{R}^{1\times 3}$ relate the joint velocity $\dot{\mathbf{q}}_\mathbf{i} \in \mathbb{R}^3$ with the i_{th} fingertip linear and rotational velocities $\dot{\mathbf{p}}_\mathbf{t_i} \in \mathbb{R}^2$ and $\omega_{\mathbf{t_i}} = \dot{\phi}_i \in \mathbb{R}$ respectively as follows:

$$\dot{\mathbf{p}}_\mathbf{t_i} = J_{v_i} \dot{\mathbf{q}}_\mathbf{i} \quad , \quad \omega_{\mathbf{t_i}} = J_{\omega_i} \dot{\mathbf{q}}_\mathbf{i} \quad (4)$$

The system dynamics under the contact and rolling constraints (1) in the gravity field is described by the following equations:

$$M_i(\mathbf{q_i})\ddot{\mathbf{q}}_\mathbf{i} + C_i(\mathbf{q_i}, \dot{\mathbf{q}}_\mathbf{i})\dot{\mathbf{q}}_\mathbf{i} + \mathbf{g_i}(\mathbf{q_i}) + D_{ii}{}^T f_i + A_{ii}{}^T \lambda_i = \mathbf{u_i}$$

$$M \begin{bmatrix} \ddot{\mathbf{p}}_\mathbf{o} \\ \ddot{\theta}_o \end{bmatrix} + \sum_{i=1}^{4} \left(D_{i5}{}^T f_i + A_{i5}{}^T \lambda_i \right) = \begin{bmatrix} 0 \\ -m_o g \\ 0 \end{bmatrix} \quad (5)$$

where $M_i(\mathbf{q_i}) \in \mathbb{R}^{3\times 3}, M = diag\,(M_o, I_o)$, with $M_o = diag\,(m_o, m_o)$ the positive definite inertia matrices of the i_{th} finger and object respectively and m_o, I_o denote the object's mass and moment of inertia and $C_i(\mathbf{q_i}, \dot{\mathbf{q}}_\mathbf{i})\dot{\mathbf{q}}_\mathbf{i} \in \mathbb{R}^3$ the vector of Coriolis and centripetal forces of the i_{th} finger. Furthermore, $\mathbf{g_i}(\mathbf{q_i}) \in \mathbb{R}^3$ is the gravity vector, g the gravity acceleration and the Lagrange multipliers f_i and λ_i represent the applied normal and tangential constraint forces respectively at the contacts. Last, $\mathbf{u_i} \in \mathbb{R}^3$ is the vector of applied joint torques to the i_{th} finger given by [1]:

$$\mathbf{u_i} = \mathbf{g_i}(\mathbf{q_i}) - k_{v_i}\dot{\mathbf{q}}_\mathbf{i} + (-1)^{i+1}\frac{f_d}{2r} J_{vi}{}^T (\mathbf{p_{t_2}} - \mathbf{p_{t_1}}) - J_{\omega_i}{}^T r \hat{N}_i + \frac{\hat{m}_o g}{2} J_{vi}{}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (6)$$

where

$$\hat{N}_i(t) = \frac{r}{\gamma_i}(\phi_i(t) - \phi_i(0)), \quad (7)$$

$$\hat{m}_o(t) = \hat{m}_o(0) - \frac{g}{2\gamma_M}\left(\mathbf{p_{t_1t_2}} - \mathbf{p_{t_1t_2}}(0)\right)^T \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad (8)$$

are the estimations of the tangential forces and object mass respectively with k_{v_i}, γ_i, γ_M being positive constant gains, $\hat{m}_o(0)$ is an initial guess of the object mass m_o, f_d is a positive constant reflecting the desired grasping force and $\mathbf{p_{t_1t_2}} \triangleq \mathbf{p_{t_1}} + \mathbf{p_{t_2}}$. After establishing an initial contact with the object, this controller achieves a stable grasp manifold by fingertip rolling in which positions and forces satisfy the following equations (subscript "∞" denotes equilibrium values).

$$f_{i\infty} = (-1)^{i+1}\frac{f_d}{2r}\mathbf{n_{ci}}^T\left(\mathbf{p_{t_2}} - \mathbf{p_{t_1}}\right) + \frac{m_o g}{2}\mathbf{n_{ci}}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix}, i = 1, 2 \quad (9)$$

$$\lambda_{i\infty} = (-1)^{i+1}\frac{f_d}{2r}\mathbf{t_{ci}}^T\left(\mathbf{p_{t_2}} - \mathbf{p_{t_1}}\right) + \frac{m_o g}{2}\mathbf{t_{ci}}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix}, i = 1, 2 \quad (10)$$

$$f_d\left(Y_{1\infty} - Y_{2\infty}\right) + \frac{m_o g \sin\theta_{o\infty}}{2}\left(Y_{1\infty} + Y_{2\infty}\right) = 0 \quad (11)$$

$$\hat{N}_{i\infty} = -\lambda_{i\infty} \quad (12)$$

$$\hat{m}_{o\infty} = m_o \quad (13)$$

$$\hat{N}_{1\infty} + \hat{N}_{2\infty} = \frac{f_d}{2r}\left(Y_{1\infty} - Y_{2\infty}\right) \quad (14)$$

$$\hat{N}_{2\infty} - \hat{N}_{1\infty} = m_o g \cos\theta_{o\infty}. \quad (15)$$

Each contact force at equilibrium compensates for half the object weight and contributes to the grasping force, while tangential force estimates converge to equilibrium values. Furthermore, mass estimates converge to the real object mass.

Adding a receiver hand to the system with $f_d = f_{init}$ and $\hat{m}_o(t) = 0$, it is proved that a new stable grasp manifold is achieved in which positions and forces satisfy the following equations.

$$f_{i\infty} = (-1)^{i+1}\mathbf{n_{ci}}^T\mathbf{F_j} + (j-1)\frac{m_o g}{2}\mathbf{n_{ci}}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (16)$$

$$\lambda_{i\infty} = (-1)^{i+1}\mathbf{t_{ci}}^T\mathbf{F_j} + (j-1)\frac{m_o g}{2}\mathbf{t_{ci}}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (17)$$

for $j = 1, 2$ with

$$\mathbf{F_j} = \begin{cases} \frac{f_{init}}{2r}\left(\mathbf{p_{t_4}} - \mathbf{p_{t_3}}\right) & , j = 1 \\ \frac{f_d}{2r}\left(\mathbf{p_{t_2}} - \mathbf{p_{t_1}}\right) & , j = 2 \end{cases}$$

Moreover

$$\hat{m}_{o\infty} = m_o \quad (18)$$

$$f_d\left(Y_{1\infty} - Y_{2\infty}\right) + f_{init}\left(Y_{3\infty} - Y_{4\infty}\right) + \frac{m_o g \sin\theta_{o\infty}}{2}\left(Y_{1\infty} + Y_{2\infty}\right) = 0 \quad (19)$$

$$\hat{N}_{1\infty} + \hat{N}_{2\infty} = \frac{f_d}{r}\big(Y_{1\infty} - Y_{2\infty}\big) \tag{20}$$

$$\hat{N}_{2\infty} - \hat{N}_{1\infty} = m_o g \cos\theta_o \tag{21}$$

$$\hat{N}_{3\infty} = \hat{N}_{4\infty} \tag{22}$$

$$2\hat{N}_{3\infty} = \frac{f_{init}}{r}\big(Y_{3\infty} - Y_{4\infty}\big) \tag{23}$$

Notice that the receiver's tangential forces at equilibrium correspond to a grasp without an object load (22)-(23) while the giver's tangential forces at equilibrium (20)-(21) correspond to those achieved for the one-hand case (14)-(15). Moreover, notice the different torque balance achieved (19) compared to the one-hand case (11).

Following a similar reasoning as in [1], using

$$\begin{aligned} V = \frac{1}{2}\Bigg(&\dot{\mathbf{x}}^T M_s \dot{\mathbf{x}} + \sum_{i=1}^{4} \gamma_i \hat{N}_i^2 + \gamma_M \Delta M^2 \\ &+ \frac{f_d}{2r}\|\mathbf{p_{t_1}} - \mathbf{p_{t_2}}\|^2 + + \frac{f_{init}}{2r}\|\mathbf{p_{t_3}} - \mathbf{p_{t_4}}\|^2\Bigg) \\ &+ m_o g \Delta y \begin{bmatrix} 0 \\ 1 \end{bmatrix} \end{aligned} \tag{24}$$

with $M_s = \operatorname{diag}(M_1, M_2, M_3, M_4, M)$, $\Delta M = m_o - \hat{m}_o$ and $\Delta y = \mathbf{p_o}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} - \frac{1}{2}(\mathbf{p_{t_1}} + \mathbf{p_{t_2}})^T \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, it is possible to prove that by appropriately choosing the control gains, (24) is locally positive definite in the constraint manifold defined by $\mathcal{M}_c(\mathbf{x}) = \{\mathbf{x} \in \mathbb{R}^{15} : A^T \dot{\mathbf{x}} = 0\}$. It is clear that $\dot{V} = -W \leq 0$ where

$$W = k_{v_1}\|\dot{\mathbf{q}}_\mathbf{1}\|^2 + k_{v_2}\|\dot{\mathbf{q}}_\mathbf{2}\|^2 + k_{v_3}\|\dot{\mathbf{q}}_\mathbf{3}\|^2 + k_{v_4}\|\dot{\mathbf{q}}_\mathbf{4}\|^2 \tag{25}$$

and consequently $V(t) \leq V(0)$ holds. The analysis concludes that $\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}$ are bounded and converge to zero.

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