A human inspired stable object load transfer for robots in hand-over tasks

Efi Psomopoulou and Zoe Doulgeri

***Abstract*— A human-inspired hand-over control strategy is proposed for the haptic interaction of two dual-fingered hands for the planar case. It is based on a grasp controller for an unknown object which achieves, via fingertip rolling, a stable grasp and a real object mass estimation. Object load transfer is receiver initiated, follows human evidence and involves awareness of the other hand's state based solely on local proprioceptive measurements. Simulation results illustrate the proposed approach.**

I. INTRODUCTION

Handing over different objects to humans is a key functionality for robots that are intended to assist or cooperate with humans in daily tasks. The level of fluency of the haptic interaction between the human and the robot is very important for the robot's natural integration in the human environment. Hence, there have been a number of human studies that analyse the process and the required features of a successful hand-over [1]–[3]. Most of the proposed robotic solutions focus on the hand-over initiation procedure using visual feedback mechanisms. The issue is then a task oriented safe grasp of an object so that it is appropriately presented to the receiver hand for the subsequent receiver's grasp to be feasible and comfortable [4]–[6]. The force and energy exchange that occurs during the haptic interaction of a hand-over task and its temporal coordination is, to our knowledge, neglected. The main phase of a hand-over task is, however, the transferring of the object's load that is usually unknown to the receiver from the giver's hand. It consists of controlling the grip and load forces in order to preserve object transfer stability and it is hence characterized by a system consisting of an object held by the fingers of two hands. In this work, we are concerned with the dynamic stability of such a system and a human inspired load transfer strategy. In our previous work [7], object load transfer is initiated by the giver in a feed forward fashion and it can be subject to failure when the receiver does not instantly accept the released load. In contrast, this work proposes a receiver initiated strategy which involves a richer haptic interaction between the hands. The analysis is here confined in the 2D space for an object with parallel surfaces but can be applied to objects of unknown shape (Fig. 1). We consider robotic hands under the control of a dynamically stable grasper with mass estimation capabilities. The proposed strategy is important for the realization of stable robot to human hand-overs particularly in elderly assistance as the robot giver ensures haptically that the receiver has stably grasped the object before opening its grip.

II. DYNAMICS 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 and moment of inertia I_o in the gravity field. The minimum set of assumptions required to achieve a stable grasp by fingertip rolling of two hands is as follows. Each hand consists of two fingers ($i = 1, 2$ for the giver, $i = 3, 4$ for the receiver) of 3 degrees of freedom 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.

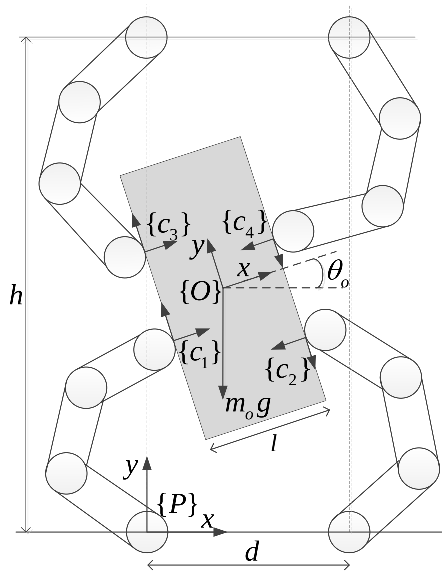

Fig. 1: System of robotic fingers grasping a rigid object with parallel surfaces

Let $\{P\}$ be the inertia frame attached at the base of the first finger and $\{O\}$ be the object frame placed at its center

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The authors are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece. emails: efipsom@eng.auth.gr, doulgeri@eng.auth.gr

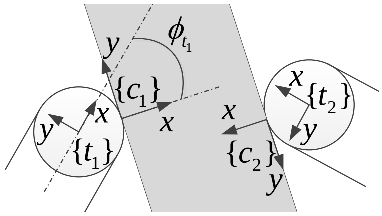

Fig. 2: Finger tip and contact frames

of mass (Fig. 1) 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 $\mathbf{p_{t_i}} \in \mathbb{R}^2$ and rotation matrix $R_{t_i} = R(\phi_i)$, with $\phi_i = \sum_{j=1}^{3} q_{ij}$. 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. Let the orientation of $\{c_i\}$ relative to $\{t_i\}$ be described by $R_{t_1c_1} = R(\phi_{t_i})$ (Fig. 2). Frame $\{c_i\}$ is described by position vector $\mathbf{p_{c_i}} \in \mathbb{R}^2$ and rotation matrix $R_{c_i} = R(\phi_i + \phi_{t_i})$. 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 $\mathbf{p_{c_i}} = \mathbf{p_{t_i}} + r\mathbf{n_{c_i}}$.

We model the system under the following contact and rolling constraints [8]:

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

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 $J_{v_i} = J_{v_i}(\mathbf{q_i}) \in \mathbb{R}^{2\times3}$, $J_{\omega_i} = J_{\omega_i}(\mathbf{q_i}) \in \mathbb{R}^{1\times3}$ 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 first equation in (1) is the contact constraint implying that the fingertip cannot penetrate or leave the object's surface. The second equation in (1) is the rolling constraint denoting that the velocity of the contact point on the fingertip surface is equal to the velocity of the contact point on the object surface and in practice implies that friction at the contact is sufficient to sustain the tangential forces needed for the rolling motion.

The system dynamics under the contact and rolling constraints (1) on the vertical plane 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 $M_i(\mathbf{q_i}) \in \mathbb{R}^{3\times3}, M = diag\,(M_o, I_o)$, with $M_o = diag\,(m_o, m_o)$ the positive definite inertia matrices of the i_{th} finger and object respectively and $C_i(\mathbf{q_i}, \dot{\mathbf{q}}_\mathbf{i})\dot{\mathbf{q}}_\mathbf{i} \in \mathbb{R}^3$ 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.

The hand-over strategy that we propose relies on the online estimation of the real object's mass and the dynamic stable grasp of an object by fingertip rolling. A controller that possesses these characteristics has been proposed by [8] for objects of unknown shape and is given by:

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

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 $\mathbf{p_{t_1t_2}} \triangleq \mathbf{p_{t_1}} + \mathbf{p_{t_2}}$. Notice that this control law does not require any information on exact contact locations, contact forces and object weight. After establishing an initial contact with the object, this controller achieves a stable grasp equilibrium by fingertip rolling.

The main hand-over phase starts with the receiver coming into an initial contact with the object which has been stably grasped by the giver under the control of (6)-(8). As described in Section III, our proposed strategy ensures that the receiver has stably grasped the object before opening its grip. This is dependent on the existence of a stable equilibrium when the object is grasped by two hands, which is analysed in this section.

System Equilibrium: We consider a robotic receiver under the control law (6)-(8) with $f_d = f_{init}$ and $\hat{m}_o(t) = 0$. Substituting the control law (6)-(8) into (5) utilizing (2), (3), the closed loop system can be written in terms of the force and object mass errors as follows:

$$M_i\ddot{\mathbf{q}}_\mathbf{i} + C_{f_i}\dot{\mathbf{q}}_\mathbf{i} + D_{ii}{}^T\Delta f_i + A_{ii}{}^T\Delta\lambda_i + rJ_{\omega_i}{}^T\Delta N_i \quad , j = 1, 2$$
$$+ (j-1)\Delta M\frac{g}{2}J_{vi}{}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} = 0 \quad (9)$$

$$M_o\ddot{\mathbf{p}}_\mathbf{o} - \sum_{i=1}^{4}(\mathbf{n_{c_i}}\Delta f_i + \mathbf{t_{c_i}}\Delta\lambda_i) = 0 \quad (10)$$

$$I_o\ddot{\theta}_o+\sum_{i=1}^{4}\hat{p}_{oc_i}^T(\mathbf{n_{c_i}}\Delta f_i+\mathbf{t_{c_i}}\Delta\lambda_i)+S_N=0 \quad (11)$$

where $C_{f_i}=(C_i+k_{v_i}I_3)$ with I_3 being the identity matrix of dimension 3 and the rest of the terms are given by the following equations

$$\Delta f_i = f_i-(-1)^{i+1}\mathbf{n_{ci}}^T\mathbf{F_j}-(j-1)\frac{m_o g}{2}\mathbf{n_{ci}}^T\begin{bmatrix}0\\1\end{bmatrix} \quad (12)$$

$$\Delta\lambda_i = \lambda_i-(-1)^{i+1}\mathbf{t_{ci}}^T\mathbf{F_j}-(j-1)\frac{m_o g}{2}\mathbf{t_{ci}}^T\begin{bmatrix}0\\1\end{bmatrix} \quad (13)$$

$$\Delta N_i = \hat{N}_i+(-1)^{i+1}\mathbf{t_{ci}}^T\mathbf{F_j}+(j-1)\frac{m_o g}{2}\mathbf{t_{ci}}^T\begin{bmatrix}0\\1\end{bmatrix} \quad (14)$$

$$\Delta M = m_o-\hat{m}_o \quad (15)$$

$$\begin{aligned}S_N &= \frac{f_d}{2r}\left(\hat{p}_{oc_1}^T-\hat{p}_{oc_2}^T\right)\left(\mathbf{p_{t_2}}-\mathbf{p_{t_1}}\right)\\ &+\frac{m_o g}{2}\left(\hat{p}_{oc_1}^T+\hat{p}_{oc_2}^T\right)\begin{bmatrix}0\\1\end{bmatrix}\\ &+\frac{f_{init}}{2r}\left(\hat{p}_{oc_3}^T-\hat{p}_{oc_4}^T\right)\left(\mathbf{p_{t_4}}-\mathbf{p_{t_3}}\right)\end{aligned}$$

with

$$\mathbf{F_j}=\begin{cases}\frac{f_{init}}{2r}\left(\mathbf{p_{t_4}}-\mathbf{p_{t_3}}\right) & ,j=1\\ \frac{f_d}{2r}\left(\mathbf{p_{t_2}}-\mathbf{p_{t_1}}\right) & ,j=2\end{cases} \quad (16)$$

In order to find the equilibrium state of the system in the end of this stage, we set velocities and accelerations to zero in (9):

$$D_{ii}^T\Delta f_i+A_{ii}^T\Delta\lambda_i+J_{\omega_i}^T r\Delta N_i+(j-1)\Delta M\frac{g}{2}J_{vi}^T\begin{bmatrix}0\\1\end{bmatrix}=0$$

which using (2), (3) can be written as:

$$\begin{bmatrix}J_{v_i}^T & J_{\omega_i}^T\end{bmatrix}\begin{bmatrix}\mathbf{n_{ci}}\Delta f_i+\mathbf{t_{ci}}\Delta\lambda_i+(j-1)\Delta M\frac{g}{2}\begin{bmatrix}0\\1\end{bmatrix}\\ r(\Delta\lambda_i+\Delta N_i)\end{bmatrix}=0$$

Assuming a full rank Jacobian matrix $J_i=\begin{bmatrix}J_{v_i}^T & J_{\omega_i}^T\end{bmatrix}$, we obtain

$$\mathbf{n_{ci}}\Delta f_i+\mathbf{t_{ci}}\Delta\lambda_i+(j-1)\Delta M\frac{g}{2}\begin{bmatrix}0\\1\end{bmatrix}=0 \quad (17)$$

$$\Delta\lambda_i+\Delta N_i=0 \quad (18)$$

Adding equations (17) for all i and j and substituting the object's translational motion equation (10) at equilibrium ($\ddot{\mathbf{p}}_\mathbf{o}=0$) yields

$$\Delta M=0 \quad (19)$$

and $\mathbf{n_{ci}}\Delta f_i+\mathbf{t_{ci}}\Delta\lambda_i=0$ that owing to the independent directions leads to:

$$\Delta f_i=\Delta\lambda_i=0 \quad (20)$$

Consequently, (18) yields

$$\Delta N_i=0 \quad (21)$$

Given (20), the object's rotational motion equation (11) at equilibrium ($\ddot{\theta}_\mathbf{o}=0$) yields a zero rotational torque acting at the object

$$S_N=0 \quad (22)$$

From (19) - (21), it is clear that all force and object mass errors are zero at equilibrium. Specifically, (19) implies that, at equilibrium, the giver estimates correctly his object load while from (21) we conclude that both giver and receiver estimate the actual tangential forces at the fingertips. Moreover, (20) yields for $j=1,2$:

$$f_{i\infty}=(-1)^{i+1}\mathbf{n_{ci}}^T\mathbf{F_j}+(j-1)\frac{m_o g}{2}\mathbf{n_{ci}}^T\begin{bmatrix}0\\1\end{bmatrix} \quad (23)$$

$$\lambda_{i\infty}=(-1)^{i+1}\mathbf{t_{ci}}^T\mathbf{F_j}+(j-1)\frac{m_o g}{2}\mathbf{t_{ci}}^T\begin{bmatrix}0\\1\end{bmatrix} \quad (24)$$

where the "∞" subscript denotes equilibrium values, implying that contact forces (23), (24) compensate for half the object weight and contribute to the grasping force.

Expressing (22) in the object frame and assuming an object with parallel surfaces to simplify the analysis, utilizing (16) and the contact constraints, the torque balance achieved yields the following equation regarding contact positions at equilibrium:

$$\begin{aligned}&f_d\left(Y_{1\infty}-Y_{2\infty}\right)+f_{init}\left(Y_{3\infty}-Y_{4\infty}\right)+\\ &+\frac{m_o g\sin\theta_{o\infty}}{2}\left(Y_{1\infty}+Y_{2\infty}\right)=0\end{aligned} \quad (25)$$

Notice the similarities between this relationship and the one which holds for one hand grasp [8]:

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

Furthermore, adding equations (21) for $i=1,2$ and $i=3,4$, expressing the result in the object frame, utilizing the contact constraints yields:

$$\hat{N}_{1\infty}+\hat{N}_{2\infty}=\frac{f_d}{r}\left(Y_{1\infty}-Y_{2\infty}\right) \quad (26)$$

$$\hat{N}_{2\infty}-\hat{N}_{1\infty}=m_o g\cos\theta_o \quad (27)$$

$$\hat{N}_{3\infty}=\hat{N}_{4\infty} \quad (28)$$

$$2\hat{N}_{3\infty}=\frac{f_{init}}{r}\left(Y_{3\infty}-Y_{4\infty}\right) \quad (29)$$

Notice that in the end of this stage, the receiver's tangential forces at equilibrium correspond to a grasp without an object load (28), (29) while the giver's tangential forces at equilibrium (26), (27) correspond to those achieved for the one-hand case [8].

Stability Analysis: We rewrite the closed loop system equation (5), (6) - (8) in the following compact form collecting all Lagrange multipliers in the vector $\boldsymbol{\lambda}=[f_1\ f_2\ f_3\ f_4\ \lambda_1\ \lambda_2\ \lambda_3\ \lambda_4]^T$ and all system position variables in $\mathbf{x}=[\mathbf{q_1}^T\ \mathbf{q_2}^T\ \mathbf{q_3}^T\ \mathbf{q_4}^T\ \mathbf{p_o}^T\ \theta_o]^T$.

$$\begin{aligned}&M_s\ddot{\mathbf{x}}+C_s\dot{\mathbf{x}}+K_v\dot{\mathbf{x}}+A\boldsymbol{\lambda}-\begin{bmatrix}\frac{f_d}{2r}J_{v1}^T(\mathbf{p_{t_2}}-\mathbf{p_{t_1}})\\ -\frac{f_d}{2r}J_{v2}^T(\mathbf{p_{t_2}}-\mathbf{p_{t_1}})\\ \frac{f_{init}}{2r}J_{v3}^T(\mathbf{p_{t_4}}-\mathbf{p_{t_3}})\\ -\frac{f_{init}}{2r}J_{v4}^T(\mathbf{p_{t_4}}-\mathbf{p_{t_3}})\\ 0_{3\times1}\end{bmatrix}\\ &+r\begin{bmatrix}\hat{N}_1J_{\omega_1}^T\\ \hat{N}_2J_{\omega_2}^T\\ \hat{N}_3J_{\omega_3}^T\\ \hat{N}_4J_{\omega_4}^T\\ 0_{3\times1}\end{bmatrix}+\begin{bmatrix}-\frac{\hat{m}_o g}{2}J_{v1}^T\\ -\frac{\hat{m}_o g}{2}J_{v2}^T\\ 0\\ 0\\ 0\\ m_o g\\ 0\end{bmatrix}=0\end{aligned} \quad (30)$$

with

$$M_s=\text{diag}\left(M_1,M_2,M_3,M_4,M\right)$$

$$C_s = \text{diag}\left(C_1, C_2, C_3, C_4, 0_{3\times 3}\right)$$
$$K_v = \text{diag}\left(k_{v_1} I_3, k_{v_2} I_3, k_{v_3} I_3, k_{v_4} I_3, 0_{3\times 3}\right)$$
$$A = \begin{bmatrix} D & B \\ D_o & B_o \end{bmatrix}$$

where $D = \text{diag}\left(D_{ii}^T\right)$, $B = \text{diag}\left(A_{ii}^T\right)$, $i = 1, \ldots, 4$,

$$D_o = \begin{bmatrix} D_{15}^T & D_{25}^T & D_{35}^T & D_{45}^T & D_{55}^T \end{bmatrix}$$
$$B_o = \begin{bmatrix} A_{15}^T & A_{25}^T & A_{35}^T & A_{45}^T & A_{55}^T \end{bmatrix}$$

Similarly, the constraints can be written compactly as: $A^T \dot{\mathbf{x}} = 0$.

Multiplying (30) by $\dot{\mathbf{x}}^T$ from the left yields: $\dfrac{dV}{dt} + W = 0$ where:

$$V = \frac{1}{2}\Bigg(\dot{\mathbf{x}}^T M_s \dot{\mathbf{x}} + \sum_{i=1}^{4} \gamma_i \hat{N}_i^2 + \gamma_M \Delta M^2 + \frac{f_d}{2r}\|\mathbf{p_{t_1}} - \mathbf{p_{t_2}}\|^2 + + \frac{f_{init}}{2r}\|\mathbf{p_{t_3}} - \mathbf{p_{t_4}}\|^2\Bigg) + m_o g \Delta y \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{31}$$

with $\Delta M = m_o - \hat{m}_o$, $\Delta y = \mathbf{p_o}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} - \frac{1}{2}(\mathbf{p_{t_1}} + \mathbf{p_{t_2}})^T \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ and

$$W = k_{v_1}\|\dot{\mathbf{q}}_\mathbf{1}\|^2 + k_{v_2}\|\dot{\mathbf{q}}_\mathbf{2}\|^2 + k_{v_3}\|\dot{\mathbf{q}}_\mathbf{3}\|^2 + k_{v_4}\|\dot{\mathbf{q}}_\mathbf{4}\|^2 \tag{32}$$

Similarly to [8], it is possible to prove that by appropriately choosing the control gains, (31) 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 $\dot{V} = -W \leq 0$ and consequently $V(t) \leq V(0)$ holds. The stability analysis follows a similar reasoning as in [8] to conclude that $\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}$ are bounded and converge to zero.

The analysis shows that the addition of the extra hand does not de-stabilize the system but the equilibrium state is different from the one achieved with one two-fingered hand.

III. RECEIVER INITIATED OBJECT TRANSFER

We propose a strategy for both a giver and a receiver robotic hand which can be applicable to human-robot interactions. The robotic giver is a stably grasping robotic hand that follows the receiver's lead who can therefore be anyone from a fully cooperative robot to an insufficiently responsive human. This is in contrast to our previous work [7], where we have proposed a giver initiated strategy assuming a fully responsive receiver. The robotic receiver implements a human inspired object load and grip function and adapts to the giver's withdrawal based on haptic clues. The object load transfer strategy for the two hands is described by Algorithms 1 and 2.

Algorithm 1 Object Load Transfer Strategy - Giver

1: **if** $\hat{m}_o(t) > 0$ **then**
2: $\quad f_d \leftarrow f_{dg}(t) = \varepsilon_g \hat{m}_o(t) + f_{end}$
3: **else**
4: $\quad$ Open grip
5: **end if**

The giver estimates the transferred object mass $\hat{m}_o$ continuously via (8) and adapts its grip force $f_{dg}(t)$ accordingly (line 2 - Algorithm 1). Once the mass estimate of the giver crosses zero from positive to negative, which means that the object load is fully transferred to the receiver, the giver withdraws completely (line 4 - Algorithm 1).

Algorithm 2 Object Load Transfer Strategy - Receiver

1: Receiver initiates transfer at time instant: t_{start}
2: $\hat{m}_o(t) \leftarrow m_r(t) = \mu(t - t_{start})$
3: $f_d \leftarrow f_{dr}(t) = \varepsilon_r m_r(t) + f_{init}$
4: **if** $\left(\dot{\mathbf{p}}_{\mathbf{t3}}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \dot{\mathbf{p}}_{\mathbf{t4}}^T \begin{bmatrix} 0 \\ 1 \end{bmatrix} > \text{threshold}\right)$ **then** ▷*haptic clue*
5: $\quad \hat{m}_o(t) \leftarrow \hat{m}_o(t)$
6: $\quad f_d \leftarrow f_{dr}(t) = \varepsilon_r \hat{m}_o(t)$
7: **end if**

The robotic receiver is the object load transfer initiator (say at t_{start}) by linearly increasing its load and grip forces, utilizing the human-inspired pre-set time functions [3] (lines 2 and 3 - Algorithm 2). As soon as there is a sudden increase of the fingertips' velocity in the gravity field above a threshold (line 4 - Algorithm 2), load and grip forces switch to the object mass estimator (8) and the grip force function (lines 5, 6 - Algorithm 2). This sudden increase of the fingertips' velocity is proposed as a haptic clue for the giver's fingers opening. In fact, when the giver's mass estimate crosses zero from positive to negative, the object load $m_r(t)$ at the receiver (line 2 - Algorithm 2) is greater than the real object load. Thus, when the giver's fingers open, there is a sudden load change perceived by the receiver as a slight 'pulling' of the object upwards. Visual feedback or multi-modal sensing may also be utilized to perceive the giver's withdrawal. As shown in Section II, the stability of the system is not compromised in cases there are periods of time where no object load transfer occurs (eg. hand-over to insufficiently responsive human).

IV. SIMULATION RESULTS

We consider two dual-fingered hands with identical robotic fingers, as depicted in Fig. 1, where $r = 0.01$ m and their parameters given in Table I. The receiver hand is placed at height $h = 0.14$ m above the giver hand while the finger base at each hand has a distance $d = 0.02$ m. We consider an object with parallel surfaces of width $l = 0.02$ m and height $1.8 * l$ m with mass $m_o = 0.08$ kg and $I_o = 4 \times 10^{-4}$ kg $\cdot$ m^2. Giver and receiver control constants are $k_{v_i} = 0.001$ Nms, $\gamma_i = 0.001$ s^2/kg for $i = 1, \ldots 4$. The giver's control parameters are given as follows: $f_d = 4.5$ N, $\gamma_M = 0.1$ m^2/(kg $\cdot$ s^2), $\hat{m}_o(0) = 0.02$ kg, $\hat{m}_o(t_{start}) = m_o$ kg, $f_{end} = 0.5$ N and $\varepsilon_g = 50$ m/s^2, where f_{end} is the grasping force at the zero crossing of the mass estimate and ε_g is a positive control constant, that should ideally be chosen or adapted to the frictional properties of the contact and its tuning is related to the system's transient performance. The receiver's parameters are given by: $f_{init} = 0.5$ N, $\mu = 0.16$ kg/s, $\gamma_M = 0.8$ m^2/(kg $\cdot$ s^2), $\hat{m}_o(t_b) = m_r(t_b)$ kg and $\varepsilon_r = 50$ m/s^2, where μ is the rate at which the receiver increases its load, t_b is the time instant when the receiver perceives the withdrawal of the giver and ε_r is a positive control constant similarly to ε_g.

Simulation results depict system response in Fig. 4 - Fig. 10 for the object load transfer process after the giver's grasp for clarity reasons. From the initial giver's grasp, only the mass estimation is shown in Fig. 3 where it is clear that the mass estimate starting from $\hat{m}_o(0) = 0.02$ kg converges to the real object mass $m_o = 0.08$ kg. At $t_0 = 5.5$ sec, the receiver is just in contact with the object held by the giver at the equilibrium state achieved after the giver's grasp. The system position at time t_0 is given in Table II. The system is allowed at this stage to reach an equilibirum after the receiver's initial contact for demonstrating results of Section II. The receiver's normal and tangential contact forces and relative contact position transients are shown in Fig. 4, Fig. 5 and Fig. 6 respectively just after t_0. Notice how the receiver's initial grasp induces a new equilibrium which is evident from the new relative contact positions of both hands (Fig. 6) and from the new object's orientation (Fig. 8).

Object load transfer occurs from $t_{start} = 6.5$ sec. Notice how during the transfer the estimated mass of the giver linearly decreases until it crosses zero and reaches a negative value (just after $t = 7$ sec - sub-plot of Fig. 7) and the giver totally releases the object. This is sensed by the receiver from the sudden increase of the velocity of the receiver's fingertips (Fig. 9). When the velocity of the receiver's fingertips exceeds a pre-set value, which in this simulation was set to 0.009 m/sec, the receiver at t_b activates the object's mass estimate (Fig. 7) and its grip force adaptation (Fig. 4, 5). The object load transfer is complete and the receiver stably grasps the object at a final equilibrium position (at approximately $t = 9$ sec in all Figures). Notice that the duration of the load and force exchange is 0.5 sec which is based on human studies [3]. Force angles (Fig. 10) stay less than 5 degrees during all stages for both hands indicating that the object is securely delivered from the giver to the receiver hand avoiding slipping even under a narrow friction cone. Joint and object velocities converge to zero at the end of the hand-over process. Fig. 11 depicts the object velocities indicating the new attained equilibrium confirming theoretical findings.

In order to demonstrate the difference between the proposed strategy and our previous strategy [7], we consider an inadequately responsive receiver who applies a small constant grasping force of $f_{dr} = 0.1$ N and takes only a quarter of the object's load $m_r = 0.02$ kg (Algorithm 2). In the giver initiated strategy [7], the receiver's force angles increase above 45 degrees (Fig. 12) which means that the object practically slips from the receiver's fingers since the giver has already released its load (Fig. 13 - dashed line). In the proposed strategy the giver guarantees the object's safe grasp by never releasing the object (Fig. 13 - solid line), hence the receiver's force angles stay less than 30 degrees (Fig. 12).

V. CONCLUSIONS

In order to ensure fluency and object stability in hand-overs, an object load transfer strategy is proposed which is related to the load and grip changes for a giver and a receiver robot hand based on human findings and haptic interaction clues. Two dual fingered hands under contact and rolling constraints in the planar case are considered. Object stability is ensured at every stage. Simulation results demonstrate the various hand-over stages. Future work includes the extension of the hand-over control strategy to the three dimensional

Links	1	2	3
Masses (Kg)	0.045	0.03	0.015
Lengths (m)	0.04	0.03	0.02
Inertias (Kg m^2) I_z $(\times 10^{-6})$	6	4	2

TABLE I: Robotic fingers parameters

Joints	$q_{i1}[deg]$	$q_{i2}[deg]$	$q_{i3}[deg]$
$i = 1$	150.725	-92.1141	-30.7137
$i = 2$	25.1163	66.9701	55.2918
$i = 3$	-131.626	53.7521	47.8739
$i = 4$	-35.8743	-52.597	-56.5287
Object	$x_o[m]$	$y_o[m]$	$\theta_o[deg]$
	0.0177	0.0635	0.0834

TABLE II: Initial system pose

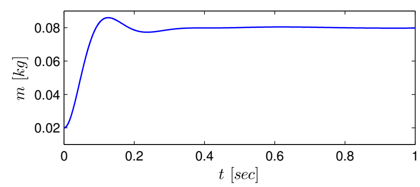

Fig. 3: Initial mass estimation by the giver

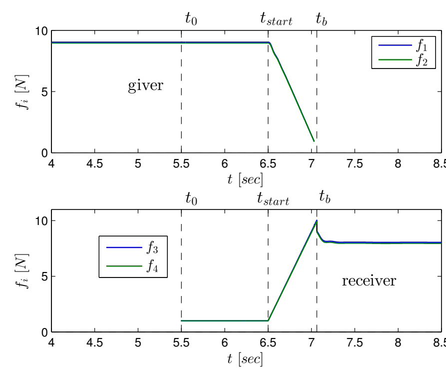

Fig. 4: Normal contact force responses

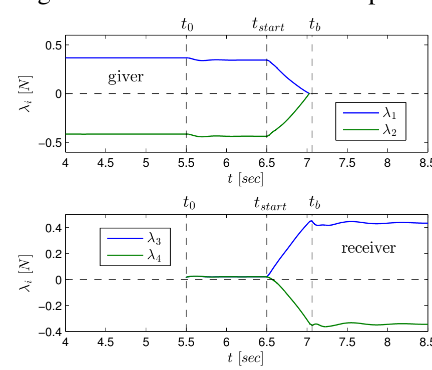

Fig. 5: Tangential contact force responses

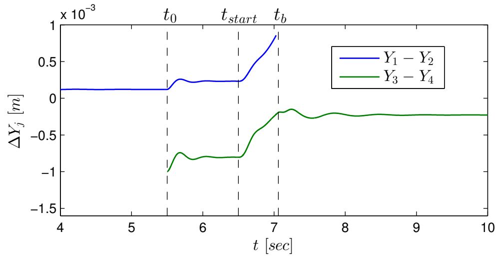

Fig. 6: Relative contact positions $Y_1 - Y_2$, $Y_3 - Y_4$

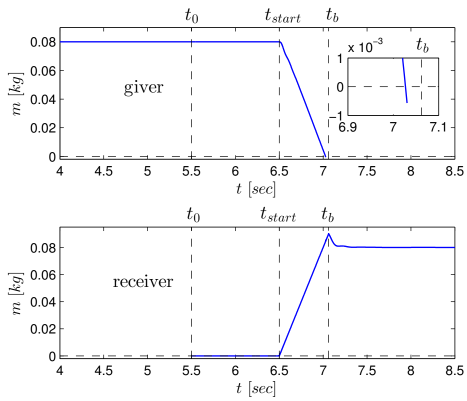

Fig. 7: Object load transfer

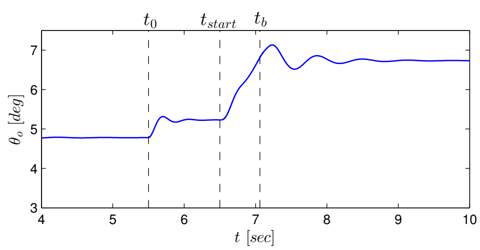

Fig. 8: Object orientation

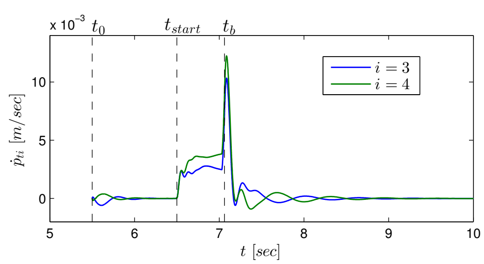

Fig. 9: Receiver's fingertip velocities

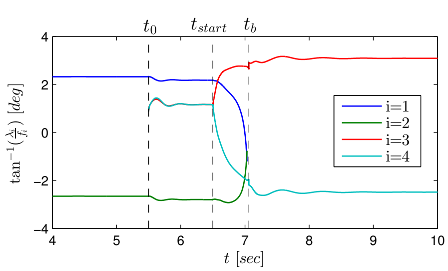

Fig. 10: Force angles

case.

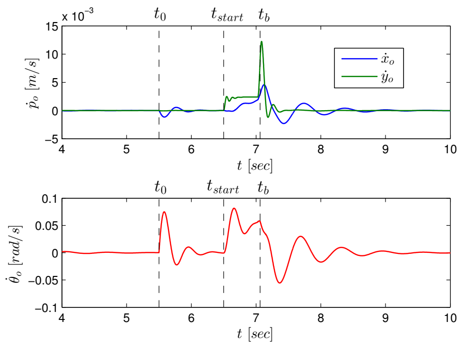

Fig. 11: Object translational and angular velocities

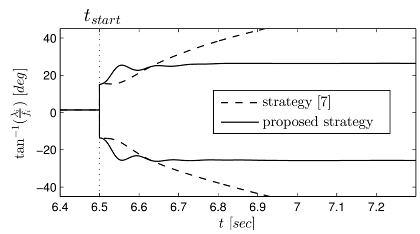

Fig. 12: An insufficiently responsive receiver's force angles with the proposed strategy (solid line) and strategy [7] (dashed line)

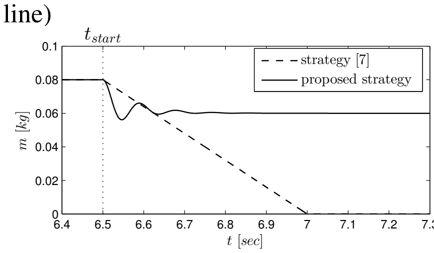

Fig. 13: The giver's object load in case of an insufficiently responsive receiver with the proposed strategy (solid line) and strategy [7] (dashed line)

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