Ability to hold grasped objects by underactuated hands: performance prediction and experiments

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Abstract—To evaluate and optimize the mechanical design of underactuated hands, a benchmark test is defined that quantifies the ability to hold grasped objects subject to force disturbances as occurs during for instance pick and place operations. The ability to hold is quantified by the magnitude of the maximum permitted static force on the center of a cylindrical object of known radius at which it can still be held within the underactuated hand. A static grasp model is developed to efficiently calculate the effect of design parameters of the hand on this maximum force. This model is applied to a planar, underactuated hand with six degrees of freedom, calculating the maximum force while the rotational joint stiffnesses and distance between the fingers was varied. We demonstrated that the rotational joint stiffness has no effect on this force, while decreasing the distance between the fingers has a negative effect. These results were validated by measurements in an experimental setup. These preliminary results show that the developed benchmark test can be effective to evaluate and optimize the performance of underactuated hands in pick and place operations.

I. INTRODUCTION

Underactuated robotic hands comprise a specific class in the field of artificial hands. Underactuated hands have more degrees of freedom (DoF) than actuators (DoA). Examples of such hands from literature are for instance the prosthetic FDD-hand [1] consisting of three actuated fingers and two passive fingers with a total of 5 DoF and only 1 DoA; the SARAH-hand [2] consisting of three fingers (10 DoF, 2 DoA); the SDM-hand [3] consisting of four fingers (8 DoF, 1 DoA); and the TWIX-hand [4], consisting of two fingers (6 DoF, 1 DoA).

Underactuated hands are especially beneficial for pick and place operations of objects of various shapes and sizes, because the fingers intrinsically adapt to the shape of the objects. In addition, they tend to be mechanically simpler, more lightweight and much easier to control compared to fully actuated hands. However, the grasp performance of underactuated hands can hardly be controlled by the actuator(s), but is mainly determined by the mechanical design [5]. Therefore, to design well-functioning underactuated hands, the performance must be addressed as a criterion early on in the mechanical design phase.

A. Literature Review on Grasp Performance

In the literature of the past decades, a large number of grasp performance metrics has already been proposed. Unfortunately, the assumptions used to quantify most conventional performance metrics are not valid for underactuated grasps [6], [7]. This is because the equilibrium conditions of the fingers cannot be satisfied by the actuation only, and the contact forces of the fingers on the object cannot be individually controlled.

In the design of underactuated hands, the following performance metrics are commonly used as design criteria:

1) Uniform or Isotropic Contact Forces [1], [8]: Normally, the relative magnitude of the contact forces of the individual phalanges on the object is strongly related to the configuration of the fingers. This metric aims to design the underactuated fingers such that the ratio of the contact force magnitudes is equal to one in any configuration.

2) Positiveness of Contact Forces [5]. Most underactuated fingers cannot be in equilibrium in every configuration, because that would require negative contact forces (i.e. pulling forces). In these situations, the fingers inevitably tend to reorientate towards a configuration without negative contact forces, which might cause a loss of the object. This metric aims to maximize the range of configurations with positive contact forces.

3) Form Closure (adapted) [7], [4]. A grasp is called form closed if the grasped object is enclosed by the fingers and cannot be moved by any disturbing force at all. For non-backdriveable underactuated fingers only, the conventional approach to determine form closure is adapted to determine the minimum number of non-backdriveable elements to obtain form closed grasps.

4) Successful Grasp Range [9], [3]. This criterion maximizes the range of positions in which the hand can be initially placed relative to an object in order to successfully grasp the object.

B. Problem and Objective

To initiate and stimulate the development of general grasp metrics, the European Robotics Research Network (EURON) proposed benchmark tests to address the magnitude of the contact forces at which objects are picked, and the maximum permitted accelerations at which an object can still be held within the hand [10]. Reviewing the current performance metrics for underactuated hands from literature, we observe that indeed the first and second metric consider the magnitude contact forces, although without considering the equilibrium conditions of grasped objects as the fourth metric does. Only the third metric considers the ability to hold objects in the hand while subject to disturbances. However,
this metric is limited to the design of non-backdriveable underactuated fingers only. Therefore, for underactuated hands in general, no performance metrics exist to address the ability to hold. For such hands, disturbances on the object can only be resisted if the relative magnitude and working direction of the contact forces change by passive reconfiguration of the fingers. This behavior to hold objects depends on the mechanical design of the finger, but has, so far, not been addressed as design criterion for underactuated hands.

The objective of this paper is to define and quantify a performance metric to evaluate the ability to hold objects by underactuated hands. In addition, we aim to predict the ability to hold as a function of design parameters by a simple model. Based on such model results, the mechanical design of underactuated hands can be optimized in an early design phase. As an example we apply the model to the design of a two-fingered hand with six DoF inspired by the pulley-tendon mechanism of Hirose and Umetani [11], and predict its performance as a function of the joint stiffnesses. In addition, an experimental setup is used to assess the performance of this hand and to verify the results predicted by the model.

II. DEFINE AND QUANTIFY PERFORMANCE

In pick and place operations, firstly equilibrium of the object to be picked must be established within the hand. This means that the equilibrium conditions of both the fingers and the object are satisfied, while compressive contact forces apply between the object and the hand. Then, the object must be held while it is subject to disturbances such as lifting from its support and accelerating by a robot arm. To define the ability to hold an object, we consider these disturbances as static forces applied to the center of mass of the object. According to the benchmark test proposal by EURON, a performance metric would then quantify the maximum disturbing force the grasp can resist. However, this maximum does not only depend on the mechanical design and control of the hand, but also on the working direction of the disturbance forces, and on the shape, size and pose of the grasped object.

To define a benchmark test for the ability to hold objects, the direction of the disturbing forces and object properties must be made explicit. To simplify testing the ability to hold, in simulation as well as in experiments, we propose to initially use (long) cylindrical objects grasped around the curved surface with their axis of symmetry normal to the grasp plane. This shape is common in daily life, has a continuous surface, is orientation independent, while the size can be described by only one variable. Ideally, the benchmark test should investigate the maximum resistive force in the working direction at which the cylinder is easiest ejected. However, this critical direction is not known a priori, and is likely to depend on the mechanical design of the hand as well. Based on the previous considerations, we propose to quantify the ability to hold by the magnitude of the maximum resisted static force $F_h$ applied to the center of a cylindrical object of known radius $r_{obj}$ while the object is constrained to move along the line of symmetry of the grasp.

III. PREDICT AND MEASURE PERFORMANCE

As a first test to predict and measure the ability to hold objects by an underactuated hand as a function of its design parameters, we initially consider a planar hand consisting of two identical fingers grasping a cylindrical object which can only move along the line of symmetry. A schematic representation of this hand with all relevant symbols is shown in Fig. 1. Each finger consists of two phalanges of length $l_i$ and is actuated by a horizontally directed constant force $F_a$ applied to the tendons at both sides. The finger mechanism is inspired by the pulley-tendon mechanism of the Soft Gripper [11], but is extended with torsion springs about the revolute joints and with a spring-loaded prismatic base joint to gain passive adjustment of the distance $B$ between the fingers and the line of symmetry.

A. Grasp Model

To predict the maximum permitted static force $F_h$ at which a cylindrical object can be hold, a simple static model is developed. In this model gravity and friction are neglected, and rigid contact points between object and fingers are assumed. After discretizing the line of symmetry, the center of the cylindrical object is placed on each grid point, and the finger configuration that encloses the object in each position is calculated. This configuration comprises the phalanx angles $\theta_i$, the contact point positions $p_i$, and the position of the proximal joint $B$, and can be found by numerically solving a set of geometric and force equalities and...
constraints (Matlab, fsolve.m). The geometric equalities of the right finger consist of two loop closure vector equations, considering the contact points at the proximal and distal phalanx, respectively, as shown in Fig. 1:

\[
\begin{align*}
(B_0^T + R_{\theta_1} (p_1^T)) & = (0_{Y_{obj}}^T) + R_{\theta_1} (0_{r_{obj}}^T) \\
(B_0^T + R_{\theta_1} (l_1^T)) + R_{\theta_2} R_{\theta_2} (l_2^T) & = (0_{Y_{obj}}^T) + R_{\theta_1} R_{\theta_2} (0_{r_{obj}}^T)
\end{align*}
\]  

(1) (2)

where \( B \) is the position of the proximal joint with respect to the global frame (capital letters); \( p_i \) is the position of the contact point with the object on the \( i^{th} \) phalanx with respect to the \( i^{th} \) local frame (small letters) while \( l_i \) is the thickness of the palhanges; \( l_1 \) is the length of the \( i^{th} \) phalanx; \( Y_{obj} \) is the position of the center of the object; \( r_{obj} \) is the radius of the object; and \( R_{\theta_i} \) represents the following rotation matrix:

\[
R_{\theta_i} = \begin{bmatrix}
\cos(\theta_i) & -\sin(\theta_i) \\
\sin(\theta_i) & \cos(\theta_i)
\end{bmatrix}
\]  

(3)

In addition to these geometric equations, the following three constraints apply in order to have contact points on the physical part of the phalanges and to avoid collision of the finger tips:

\[
0 < p_1 < l_1 \\
0 < p_2 < l_2 \\
B + \cos(\theta_1) l_1 + \cos(\theta_1 + \theta_2) l_2 > 0
\]  

(4) (5) (6)

The force equalities and constraints follow from the contact force equations, as derived by the method of virtual power according the notation of [5], but adapted to account for the prismatic joint and joint stiffnesses of the hand under consideration. The magnitude of the contact forces directed normally on the proximal phalanx (\( F_{ph1} \)), and the distal phalnax (\( F_{ph2} \)) are as follows, as derived in the Appendix:

\[
\begin{align*}
F_{ph1} = r_1 F_a - K_{\theta_1} \Delta \theta_1 - (\cos \theta_2 l_1 + p_2) F_{ph2} \\
F_{ph2} = r_2 F_a - K_{\theta_2} \Delta \theta_2 \\
\end{align*}
\]  

(7) (8)

where \( F_a \) is the actuation force; \( r_1 \) and \( r_2 \) are the radii of the proximal and distal pulley, respectively; and where \( K_{\theta_1} \) and \( K_{\theta_2} \) are the stiffnesses of the torsional springs at the rotational joints, while \( \Delta \theta_1 \) and \( \Delta \theta_2 \) are the differences between the current and initial (rest) angles of these springs. For equilibrium of the fingers, the resultant force of the actuation, linear spring force and contact forces on the prismatic joint in its moving direction must be zero, resulting in the following force equality:

\[
-F_a - K_B \Delta B + \sin(\theta_1) F_{ph1} + \sin(\theta_1 + \theta_2) F_{ph2} = 0
\]  

(9)

where \( K_B \) is the stiffness of the linear spring at the prismatic joint, and \( \Delta B \) is the difference between the current and initial length of this spring.

After numerically solving this set of geometric and force equations (1-2), (4-6), and (9), the magnitudes of the normal contact forces \( F_{ph1} (7) \) and \( F_{ph2} (8) \) are evaluated and investigated for positiveness (e.g. compressive contact forces).

When both forces are positive, a feasible power grasp is found. Otherwise, the fingers are not in equilibrium and might reconfigure to a pinch grasp in which the proximal phalanx has no contact with the object. In this case, a new solution must be found in which (1) cancels out, while (7) reduces to:

\[
F_{ph1} = 0
\]  

(10)

When for the new solution of the finger configuration, obtained with (2), (5-6), and (9-10), the magnitude of \( F_{ph2} \) is still negative, no feasible finger configuration exists for the object located on this grid point. Grasping the object on this location is impossible.

When a feasible power or pinch grasp is found, the configuration of the left finger follows from symmetry. Then the resultant of the contact forces on the object for each object position can be easily calculated:

\[
F_c = R_{\theta_1} \begin{bmatrix} 0 \\ 2F_{ph1} \end{bmatrix} + R_{\theta_1} R_{\theta_2} \begin{bmatrix} 0 \\ 2F_{ph2} \end{bmatrix}
\]  

(11)

Following this procedure for every object position finally results in a relation between the contact forces \( F_c \) on the object and its position \( Y_{obj} \) relative to the hand. Neglecting dynamics, the maximum permitted static force \( F_h \) to hold a cylindrical object is the maximum of \( -F_c \).

B. Experimental Setup

Since we considered a symmetric hand and disturbances only along the line of symmetry, the experimental setup to assess the performance can consist of only one finger while the object is supported on a linear motor. The setup we constructed is shown in Fig. 2 and is technically evaluated in [12]. The aluminum, underactuated finger was made according to the dimensions of Tab. I. The magnitude of these dimensions followed from an approximately 2:1 scaling of the human hand. The constant force actuation is mechanically obtained by attaching the cable to a spring-loaded constant force generator mechanism, and measured by a force sensor (Futek, LTH300).

To represent frictionless grasps, we made a cylindrical object consisting of two acrylic discs with a radius of 65 [mm] that can rotate independently about a vertical axis. Instead of slipping along the phalanges, the discs now roll over their contact areas, which is kinematically and kinetically equivalent to frictionless slipping along the phalanges. Hence, in this way we are able to physically emulate frictionless grasping. This object is supported and...

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>( r_1 )</td>
<td>9.95</td>
<td>radius proximal pulley [mm]</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>4.80</td>
<td>radius distal pulley [mm]</td>
</tr>
<tr>
<td>( l_1 )</td>
<td>80.0</td>
<td>length proximal phalanx [mm]</td>
</tr>
<tr>
<td>( l_2 )</td>
<td>80.0</td>
<td>length distal phalanx [mm]</td>
</tr>
<tr>
<td>( t )</td>
<td>8.50</td>
<td>thickness phalanges [mm]</td>
</tr>
<tr>
<td>( r_{obj} )</td>
<td>65.0</td>
<td>radius object [mm]</td>
</tr>
<tr>
<td>( F_a )</td>
<td>22.0</td>
<td>actuation force [N]</td>
</tr>
</tbody>
</table>
displaced by a linear motor and moved with a constant velocity of 1.76 mm/s out of the hand.

The resultant of the contact forces $F_c$ on the object in the direction of the displacement is measured by a load cell mounted between the object and the linear motor. This load cell consists of two parallel plates of spring steel such that it is only compliant in the direction of displacement. With four strain gauges (HBM, 1-LY41-3/350) glued on the parallel plates and electrically connected in a Wheatstone’s bridge configuration, $F_c$ is measured with a precision of 0.2 N at its full range. The output voltages of the force sensor and load cell are collected with a sample rate of about 100 Hz with an USB-DAQ (National Instruments, USB-6009) and using LabView 8.2.

C. Design Variables

We investigated the hand shown in Fig. 1 on the effect of the joint stiffnesses on the maximum permitted static force $F_h$ to hold the cylindrical object. Based on the grasp model as previously proposed, we calculated $F_h$ for six different cases, where the joint stiffnesses and initial angles or length were chosen according to the values shown in Tab. II. These values were based on standard available springs and were also used in the measurements. The stiffness of the prismatic joint was either infinite (blocked) or finite, while the ratio of the proximal and the distal torsional stiffnesses was approximately 1:3, 1:1, and 3:1, respectively in the six different cases studied.

The effect of the joint stiffnesses on the ability to hold was also measured with the experimental setup. For each case the torsional and linear springs of the underactuated finger were changed according to Tab. II. The measurement of the force to displace the object all the way out of the hand started each time at $Y_{obj} = 60$ mm, and stopped just before the measured $F_c$ changed sign and the object would be ejected. All measurements were repeated five times.

IV. RESULTS

The calculated curves of the resultant of the contact forces $-F_c$ of the right finger in the direction of the displacement of all six cases are given in Fig. 3. As defined in the previous chapter, the maximum permitted static force $F_h$ at which the object can be hold within the hand is the maximum of $-F_c$. The predicted and mean measured hold force $F_h$ are shown in Tab. III, where $F_h$ is normalized by the actuation force $F_a$. In addition, this table shows the predicted and measured object positions where equilibrium and the maximum hold force occurred. The standard deviation of the normalized measured forces is smaller than $0.05 \cdot 10^{-2}$.

Table III shows the differences between the predicted and measured $F_c$ is $0.27 \cdot 10^{-2}$. Also the predicted magnitudes of the contact forces $F_{ph1}$ and $F_{ph2}$ normalized to $F_a$ are shown. Comparing the experiments, significant difference in the ability to hold between cases 1-3 and 4-6 is observed. In cases 1-3 or 4-6, no significant differences in performance exist.

V. DISCUSSION

In this paper, we investigated the maximum permitted force on grasped objects as a benchmark test for the performance of underactuated hands. As shown in Fig. 3 and 4, indeed a finite force is required to displace and extract the cylindrical object out of the hand. The curve of $F_c$ as a function of the object displacement can be interpreted as follows. The intersections of this curve with the horizontal axis are the equilibrium positions: the resultant of the contact forces is zero. The first intersection from the origin, where
**V. Conclusions**

In this paper, a benchmark test was defined that quantifies the ability to hold grasped objects in an underactuated hand during pick and place operations. The ability to hold is defined as the magnitude of the maximum permitted static force on the center of a cylindrical object of known radius at which it can be resisted within the underactuated hand. A static grasp model is developed to calculate this maximum force. This model takes into account that underactuated fingers intrinsically adjust when the object is disturbed, in order to obtain a new equilibrium in a new configuration.

We demonstrated for a planar, symmetrical hand that the force to displace the object out of the hand along the line of symmetry can be efficiently calculated based on the newly developed grasp model. Differences between the
calculated and the mean measured maximum permitted force were less than 0.4% of the actuation force. Calculations and experiments showed that the distance between the fingers has a considerable effect on the ability to hold, while the relative stiffness of the rotational joints as design parameter seems to have no significant effect. The developed benchmark test to quantify the ability to hold objects can be effective to evaluate and optimize the performance of underactuated hands for pick and place operations.

ACKNOWLEDGMENT

This work has been carried out as part of the FALCON project under the responsibility of the Embedded Systems Institute with Vanderlande Industries as industrial partner. This project is partially supported by the Netherlands Ministry of Economic Affairs under the Embedded Systems Institute (BSIK03021) program.

APPENDIX

The contact force equations of the underactuated fingers of the hand shown in Fig. 1 are derived by the method of virtual power according to the notation of [5]. According to this method, the sum of virtual power of the actuation ($P_a$), the springs ($P_s$) and the contact forces on the phalanges and prismatic joint ($P_c$) must be equal zero for equilibrium:

$$\delta P_a + \delta P_s + \delta P_c = 0$$

(12)

where $\delta P$ is a function of the virtual velocities of the three degrees of freedom in the rotational joints ($\delta \theta_1$, $\delta \theta_2$), and the prismatic joint ($\delta B$). The virtual power of the actuation force ($P_a$) is:

$$\delta P_a = \begin{bmatrix} F_a & r_1 & r_2 & -1 \end{bmatrix}^T \begin{bmatrix} \delta \dot{\theta}_1 \\ \delta \dot{\theta}_2 \\ \delta B \end{bmatrix}$$

(13)

where $F_a$ is the actuation force, $r_1$ and $r_2$ are the radii of the proximal and distal pulley, respectively. The virtual power in the stiffness elements ($P_s$) equals:

$$\delta P_s = - \begin{bmatrix} K_{\theta_1} \Delta \theta_1 \\ K_{\theta_2} \Delta \theta_2 \\ K_B \Delta B \end{bmatrix}^T \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta \dot{\theta}_1 \\ \delta \dot{\theta}_2 \\ \delta B \end{bmatrix}$$

(14)

where $K_{\theta_1}$, $K_{\theta_2}$, and $K_B$ are the stiffnesses of the torsional springs at the rotational joints and the stiffness of the linear spring at the prismatic joint, respectively, while $\Delta \theta_1$, $\Delta \theta_2$, and $\Delta B$ are the difference between the current and initial (rest) angles or length of those springs. The virtual power of the normal contact forces on the phalanges and the prismatic joint ($P_c$) is the following:

$$\delta P_c = - \begin{bmatrix} P_{ph1} \\ P_{ph2} \\ P_{pr} \end{bmatrix}^T \begin{bmatrix} \delta \dot{\theta}_1 \\ \delta \dot{\theta}_2 \\ \delta B \end{bmatrix}$$

(15)

where $F_{ph1}$ and $F_{ph2}$ are the contact forces normally directed on the phalanges, $F_{pr}$ is the reaction force on the prismatic joint parallel to its DoF, and where $J$ is the matrix to transform the virtual velocities of the contact points to $\delta \dot{\theta}_1$, $\delta \dot{\theta}_2$, and $\delta B$:

$$J = \begin{bmatrix} -p_1 & 0 & \sin(\theta_1) \\ -p_2 - l_1 \cos(\theta_2) & -p_2 & \sin(\theta_1 + \theta_2) \\ 0 & 0 & 1 \end{bmatrix}$$

(16)

The contact forces are found by substituting (13)-(16) into (12), which results into the force equations in (7), (8), and (9).

REFERENCES


