Vision based techniques for the experimental characterization of a prosthetic finger model

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Abstract. Several prototypes of mechanical fingers composing anthropomorphic prosthetic hands have been developed using underactuated mechanisms. These mechanisms require specific experimental procedure to measure their properties. Due to their low weight, the addition of further sensors for measurement purposes could modify the trajectory of the single parts and the overall prosthetic device behaviour. Vision system methods represent a route to overcome these drawbacks. In this study, an experimental methodology to acquire the dynamics of an underactuated prosthetic finger is presented due to the employment of a vision-based technique, the Digital Image Correlation. The experimental characterization aids the development of a dynamical model of the finger behaviour.

1. Introduction
Much effort has been done in increasing the simplicity in the design of prosthetic hands, in order to reduce both the complexity in the control and the overall prototyping cost. In this direction, several mechanical hands specifically designed for prosthetic applications have emerged. Some of these hands are underactuated i.e. mechanisms in which the total number of actuators is lower than the number of degrees of freedom [1,2]. For underactuated mechanisms, the experimental measurements, such as the study of their dynamics, require instrumentations that do not affect the original motion of their small components. Due to their low weight, it is not a feasible approach to add further sensors to the prosthetic device only for measurement purposes. Indeed, the sensors could modify, with their own weights, the trajectory of the single parts and, consequently, the overall behavior of the prosthetic device. Besides the weight increase, the addition of multiple measurement sensors leads to an obvious growth of the design cost. Nevertheless, in the research and development stages, it is essential to gain more and more quantitative data that are associated to the movements of the whole device as well as the single components.

For what concern simulation approaches, specific tools have emerged to study the grasping of robotic hands and manipulators. The multibody model has been adopted to predict the dynamics of these systems and even for the human body simulations [3,4]. The reliability of the multibody models could be also increased by matching experimental data.

Vision-based techniques can be a valuable tool to acquire quantitative experimental data avoiding the drawbacks connecting to the underactuated feature of a mechanism and improving the robustness of theoretical models.
Digital Image Correlation (DIC) is a full-field image analysis method. It is based on grey value digital images, that can determine the contour and the displacements of an object. It is normally used to determine material properties, to study the fracture mechanics and to measure the deformation under load in three dimensions. Due to the capability of DIC to follow the dynamics of an object and reconstruct the 3D external surface, we have adapted this technique to record the prosthetic finger dynamics during a closing sequence.

In the following paragraphs, we will describe an experimental procedure applied to study the dynamics of a finger that is part of a mechanical hand. This hand is an anthropomorphic device developed for prosthetic purposes at the Department of Industrial Engineering of the University of Naples “Federico II” (Italy) [5]. In this respect, we have already demonstrated that a low-cost vision instrumentation like the Microsoft Kinect can be used to acquire the finger poses with the limitation of static configurations [6]. This current activity aims to define a dynamical model of the finger that can aid the design but also the control of the finger and, subsequently, of the whole prosthetic hand. The methodology is summarized in the scheme in Figure 1.

![Figure 1. Schematic representation of the adopted methodology.](image)

### 2. Experimental setup

The mechanical finger (Figure 2) has an anthropomorphic design and it is constituted by three phalanges (proximal, medial and distal). Two inextensible wires represent the traction and the antagonist tendons. The finger is an underactuated system since a single actuator controls the movement of three phalanges.

![Figure 2. The mechanical finger prototype.](image)

The finger prototype is 3D printed in polymeric material and it is mounted on a rigid support through the proximal phalanx. In the experimental setup, Figure 3 left side, an analog servomotor moves a pulley and, as consequence, produces the displacement of the two tendons. The myRIO Embedded Device (National Instruments) controls the servomotor rotation. Moreover, the experimental setup is equipped with an encoder to measure the motor angular position.
The vision instrumentation for the acquisition procedure are two DIC systems. The first system is the DANTEC Dynamics Q-450 equipped with two 1 MPx cameras for fast acquisition (3.3 GPx/sec), Figure 3 right side. The second one is the DANTEC Dynamics Q-400 equipped with two 5 MPx camera. As a preliminary operation, random patterns of markers have been applied on each phalanx. The acquisition has been performed during the finger closure sequence at 250 Hz (for Q-450) and at 20 Hz (for Q-400), setting the finger closing times at 1s, 2s, 3s, 4s, 6s.

**Figure 3.** The acquisition setup: the mechanical finger and the Digital Image Correlation system.

The Istra 4D software (DANTEC Dynamics) records the three-dimensional shape of the finger external surface over time (Figure 4) and allows visualizing the displacements as color maps on the three-dimensional model of the finger.

**Figure 4.** Finger frames during the acquisition procedure.

3. **Procedure to measure the phalanx rotations**
   From the instrumentation software, it is further possible to export the displacement data and the coordinates of the points belonging to the random patterns. These data allow measuring the angles between the phalanges over time during a closure sequence according to the following procedure.
For a generic point \( P \) belonging to a rigid body, as represented in Figure 5, the transformation from the \( E_{uvw} \) local frame to the \( O_{xyz} \) global frame is described by the following equation (1):

\[
\begin{pmatrix}
P_x \\
P_y \\
P_z
\end{pmatrix}
= 
\begin{pmatrix}
t_{11} & t_{12} & t_{13} & E_x \\
t_{21} & t_{22} & t_{23} & E_y \\
t_{31} & t_{32} & t_{33} & E_z
\end{pmatrix}
\begin{pmatrix}
P_u \\
P_v \\
P_w
\end{pmatrix}
\]

(1)

where \( t_{ij} \) (with \( i,j=1:3 \)) are 9 parameters composing the rotation submatrix and \( E_x, E_y, E_z \) are the coordinates of the local frame origin. To identify this transformation, the knowledge of at least four points is needed. The solution problem is a 12-equation system in 12 variables. To assure the accuracy of the calculation, it is necessary to perform an optimization procedure. Nine points (colored circles in Figure 6) belonging to the random patterns were chosen for each phalanx, leading to a 27-equation system in 12 variables.

\[ \text{Figure 5. Local frame and global frame associated to a rigid body.} \]

The coordinates of such points have been transformed from the local frame of each phalanx (the reference systems \( O_pX_pY_pZ_p \), \( O_mX_mY_mZ_m \) and \( O_dX_dY_dZ_d \) represented in Figure 6) to the global frame (the reference system \( O_MX_MY_MZ_M \) in Figure 6).

\[ \text{Figure 6. Reference systems adopted for the procedure to compute the phalanx rotation of the mechanical finger.} \]

In this way, we have obtained an experimental measurement of the phalanx rotations in time in a global reference system. These data represent a quantitative measurement of the mechanical finger dynamics. It would be also possible to add the experimental results in simulation model [7,8], for validation and improvement, to better approximate the actual system behavior.
4. Results
In Figure 7, we have reported the experimental rotations of the three phalanges as a function of the actuator tendon displacement, starting from the data acquired through the fast instrumentation (acquisition at 250 Hz). The above-described procedure can reconstruct the phalanx trajectories for the different finger closing time intervals.
In Figure 8, we have reported the digital image correlation results for the slow acquisition instrumentation just for 6 s, 4 s and 3 s. For the slow acquisition system (acquisition at 20 Hz), the procedure is less accurate in reconstructing the phalanx trajectories at short closure times (2 s and 1 s) because the image correlation is computed on consecutive frames in which there is a low similarity.

![Figure 7. Phalanx rotations with respect to the motor rotations measured at different closure times acquired through DIC Q-450.](image1)

![Figure 8. Phalanx rotations with respect to the motor rotations measured at different closure times acquired through DIC Q-400.](image2)

5. Analytical expression of phalanx rotations
The experimental data, acquired through the two vision instruments, have been fitted to find an analytical expression describing the phalanx rotations as a function of the tendon displacement. Looking at the experimental profiles, the sum of three consecutive straight lines seems to be a reasonable choice to fit the data.
The adopted function is the following 7-parameter expression:

\[ y = m1\left\{\frac{(x+a)-|x-a|}{2}\right\} + q + m2\left\{\frac{(x+b)-|x-b|}{2}\right\} + m3\left\{\frac{(x+c)-|x-c|}{2}\right\} \]  

\[ \text{(2)} \]

where \( x \) is the tendon displacement and \( m1, m2, m3, a, b, c \) and \( q \) are the parameters. The expression (2) along with the graphical meaning of the 9 parameters, that will be discussed in the following lines, are represented in Figure 9.

\[ \text{Figure 9. Graphical representation of the fitting parameters for the sum of three consecutive straight lines described by the expression (2).} \]

It is possible to define three functions, \( p(x), m(x), d(x) \), that are respectively the expressions describing the rotation of the proximal, the medial and the distal phalanges as a function of the actuator tendon displacement, \( x \). Tables 1, 2 and 3 report the coefficient values of the equation (2) for the functions associated to each phalanx. The coefficient subscripts \( p, m \) and \( d \) specify the proximal, the medial and the distal phalanx. It is worth to notice that in every case, the fitting coefficients of determination (R-squared) assume values close to 1.

\[ \text{Table 1. Proximal fitting coefficients for the different closing velocities.} \]

| Closure time | Proximal fitting coefficients for \( p(x) \) function | \( R^2 \) |
|--------------|-----------------------------------------------|----------|
| 6 s          | \( a_p \) 10.9 \( b_p \) 31 \( c_p \) 5.292 \( m1_p \) 0.03277 \( m2_p \) 20 \( m3_p \) \( q_p \) 20 | 0.9986 |
| 4 s          | \( a_p \) 11.1 \( b_p \) 31 \( c_p \) 5.203 \( m1_p \) 0.02856 \( m2_p \) 20 | 0.9989 |
| 3 s          | \( a_p \) 11.4 \( b_p \) 33 \( c_p \) 5.071 \( m1_p \) 0.03455 \( m2_p \) | 19.99 | 0.999 |
| 2 s          | \( a_p \) 11.55 \( b_p \) 33 \( c_p \) 5.008 \( m1_p \) 0.03064 \( m2_p \) | 19.99 | 0.9995 |
| 1 s          | \( a_p \) 11.72 \( b_p \) 33 \( c_p \) 4.947 \( m1_p \) 0.02613 \( m2_p \) | 19.99 | 0.9968 |
Table 2. Medial fitting coefficients for the different closing velocities.

| Closure time | Medial fitting coefficients for m(x) function | R-squared |
|--------------|---------------------------------------------|-----------|
| 6 s          | a_m 11.14 b_m 21.34 c_m 34.5 m1_m 0.107 m2_m 7.347 m3_m 0.04604 q_m 15 | 0.9989    |
| 4 s          | a_m 11.29 b_m 22.02 c_m 25 m1_m 0.1422 m2_m 6.952 m3_m 0.1121 q_m 14.98 | 0.9994    |
| 3 s          | a_m 11.6 b_m 22.76 c_m 25 m1_m 0.22 m2_m 6.704 m3_m 0.1332 q_m 14.14 | 0.9979    |
| 2 s          | a_m 11.8 b_m 22.4 c_m 25 m1_m 0.2884 m2_m 7.008 m3_m 0 q_m 14.81 | 0.9997    |
| 1 s          | a_m 12 b_m 22.6 c_m 25 m1_m 0.3087 m2_m 6.972 m3_m 0 q_m 14.62 | 0.9992    |

Table 3. Distal fitting coefficients for the different closing velocities.

| Closure time | Distal fitting coefficients for d(x) function | R-squared |
|--------------|---------------------------------------------|-----------|
| 6 s          | a_d 22.19 b_d 32.61 c_d none m1_d 0.03764 m2_d 7.73 m3_d none q_d 10.25 | 0.9929    |
| 4 s          | a_d 22.5 b_d 32.04 c_d none m1_d 0 8.316 m2_d none m3_d none q_d 10.18 | 0.9937    |
| 3 s          | a_d 23 b_d 31.68 c_d none m1_d 2.16E-05 m2_d 8.617 m3_d none q_d 10.04 | 0.9933    |
| 2 s          | a_d 23.52 b_d 33 c_d none m1_d none m2_d 8.52 m3_d none q_d 10.44 | 0.9995    |
| 1 s          | a_d 24.28 b_d 33 c_d none m1_d none m2_d 9.25 m3_d none q_d 10.4 | 0.9965    |

In this way, we have studied the effect of closure velocity on the phalanx dynamics. For the proximal phalanx, the b_p parameter assumes higher values for smaller finger closure time and, consequently, the m1_p parameter decreases.

For the medial phalanx, both the a_m and b_m parameters increase with the finger closing velocity. At the same time, we have noticed an increase in the first section slope, a_m parameter, to mean that the higher velocity leads the medial phalanx to move simultaneously to the proximal phalanx.

For the distal phalanx, the second section initial point (a_d) occurs at higher displacement values with the closure velocity. Therefore, the slope of the second section (m2_d) increases to compensate for the displacement delay and conclude the closure in the expected time. The above-mentioned parameters follow a linear trend with the closing time decrease. Fitting these parameters with a linear law, we have identified a general expression for each phalanx to account for the finger closure time, t_c, dependence (see Table 4). We have considered the remaining parameters assuming the mean values over the finger closure time. Table 4 represents an experimental dynamical model of the underactuated tendon driven finger.

Table 4. General expression parameters for the phalanx dynamics with finger closure time.

| Phalanx | General expression parameters as function of closure time |
|---------|---------------------------------------------------------|
| Proximal | a_p none, b_p -0.17 t_c +11.88, c_p 32.00, m1_p none, m2_p 0.072 t_c -4.87, m3_p 0.031, q_p 20.00 |
| Medial  | a_m -0.18 t_c +12.14, b_m 22.22, c_m 26.90, m1_m -0.044 t_c +0.35, m2_m 6.99, m3_m 0.059, q_m 14.71 |
| Distal  | a_d -0.41 t_c +24.42, b_d 32.46, c_d none, m1_d 0.013, m2_d -0.27 t_c +9.35, m3_d none, q_d 10.26 |

6. Conclusions

The employment of vision techniques represents a promising approach in the experimental characterization of small prosthetic components. The vision-based methods avoid the addition of further sensors and weights to the mechanical system.

In this study, we have probed the possibility to apply the Digital Image Correlation to acquire the dynamics of a mechanical finger. We have used two DIC systems with different features, a slow and a
fast acquisition instrument. Both the systems can give back the dynamics of the three phalanges. The slow acquisition instrument is not able to correctly reconstruct the dynamics for short closure time i.e. for higher velocity dynamics. Moreover, the acquired data have been used to identify analytical expressions describing the phalanx dynamics and correlate the behavior of each phalanx with the finger closure time. In this way, it was possible to obtain an experimental dynamical model of the finger. The described approach represents a methodology to study the dynamical behavior of the mechanical finger system that can eventually aid its control improvement.

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