Sensing Feedback for the Control of Multi-joint Prosthetic Hand

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Abstract. The paper presents a design of a sensory system for a model of a hand prosthesis. The system is based on pressure sensors modules that detect a touch with an object, and measure a contact force. First tests show that the sensors are capable to detecting slippage of an object. Kinematic simulations in a CAD program for typical grasps of reference objects made it possible to determine size, shape and placement of the sensors. The developed sensors were integrated with the hand, and preliminary experiments with grasping of various objects were conducted.

1 Introduction

In a construction of a bioprosthesis of a hand two major tasks must be solved: a design of a human-machine interface to recognize the person's intentions, and a design of an autonomic effector device which will execute those intentions.

The tasks of the interface is to measure biosignals coming from a human body during its activity and to transform them into discrete control commands [20]. The commands correspond to the objectives of the prosthesis user. At the decision level of the prosthesis control system biosignals are transformed to control commands. A variety of input signals are used at the decision level: electromyographic (EMG), mechanomyographic (MMG), electroencephalographic (EEG) [19]. After signal acquisition they are analyzed to reduce dimension of the signals through feature extraction. Existing approaches to signal analysis, based on various domains of signals: frequency – Short-Time Fourier Transform (STFT), time and frequency – Discrete Wavelet Transform (DWT) [3]. Features then go through feature selection and transformation process by means of methods like Principal Component Analysis (PCA) [7] or Tensor Factorizations (TF) [4]. The last stage of the decision process is the control decision – a result of selection of the expected move [10].

The main task of the effector device (which is usually a multi-articulated mechanism) is a physical execution of the recognized intentions. The control algorithms form a motoric level of the prosthesis control system allowing interactions with external objects: touching, grabbing and manipulation. Usually these operations are complex as a single command requires a multi-stage motion process. In advanced devices a sensory system with its own processing unit provides some level of autonomy of motions. Major disadvantages of modern hand

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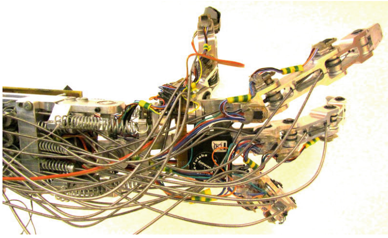


Fig. 1. Hand mechanical model, back side

prostheses are their weight and a lack of feedback from grasped objects. As a result, about half of amputees does not use their prostheses in everyday routine [2]. The first of those drawbacks may be reduced firstly by the use of new, lightweight construction materials and, secondly, by energy-efficient actuators and power sources. The latter problem is particularly nagging as it limits the set of objects that can be safely and efficiently operated with an artificial hand. Within a control systems of hand prostheses, sensory feedback is present at several levels. At the level of posture fitting, it is used to match a prosthesis configuration to the shape and the size of the grasped object [11]. This function may be realized by relatively simple binary contact detectors. The next is a force feedback which allows levelling pressure applied to an object from all contact points and control of the force used to grasp the object. This requires more advanced sensors to measure force between the hand and the object. The third level is related to transmitting feeling of a grasp and other modalities, like type of object surface, its temperature and so on to the user. This level allows increasing the precision and comfort of grasp control. In embodiments of the sensory interface dominate the non-invasive methods: electrical [1,8], and mechanical stimulation [5,12]. Independently the work on the implantation of electrodes transmitting sensory sensations directly to the residual nerves in the amputated limb is undertaken [13,15].

This work presents further development of the prosthesis presented in [18]. The capabilities of the mechanical construction were enhanced by the newly designed sensors that replaced simple binary touch detectors. The sensor modules presented in this paper base on pressure sensors and allow receiving force feedback during object grasping.

2 Hand Model

2.1 Hand Mechanics

The model of the prosthesis is equipped with 4 digits (a thumb and 3 fingers) and 13 degrees of freedom (see Fig. 1). Each finger has 4 joints driven by 3 actuators (third and fourth joints are mechanically coupled). All 4 joints of the thumb are driven independently. Joints are driven with 13 Futaba S3150 servo motors. Except the thumb base (thumb joint 0) that is driven directly by a motor mounted in a palm, the remaining 12 motors are placed in a forearm and drive is transmitted to the joints by Bowden cables with 1:1 ratio. All joints are equipped with pulse encoders to provide feedback with real joints orientations.

2.2 Sensory System

The main task of the hand sensory system is to measure interactions between the cybernetic hand and gripped (and then – held) object. The sensors used in the system should inform about the fact of a contact with an object (touch), measure the forces between the hand and the object and in the future – provide information on the tangential motion of the touched or gripped object (slippage).

Size, shape and placement of the sensors mounted on the hand should allow contiguity of all contact points with the object. While for arbitrary object it is too strong to demand and hard to achieve under the constrains of hand kinematics, we limit the project to the set of objects and types of grasp that seem typical in prosthesis use. Verification of the grasp capabilities was made for a set containing: a glass (cylindrical grasp), a tennis ball (spherical grasp), mug with a handle (hook grasp), small ball/credit card (tip/pinch grasp), a mug with a handle (hook grasp) – see Fig. 2. These objects were used as reference, however the results are valid for other objects of similar shapes and sizes.

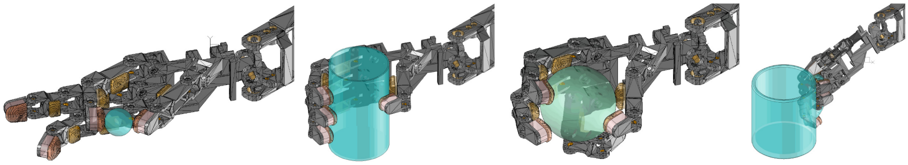


Fig. 2. Simulation results – grasps of reference objects: tip/pinch, cylindrical, spherical and hook

Before the real sensors were designed, all elements of the hand and motion of kinematic pairs were modelled in TopSolid software to determine possible location and dimensions of the sensors. Using the reference objects (see Fig. 2) and virtually testing their grasping, we analyzed space available for sensors according to the following criteria:

– sensors do not limit mobility of the joints (reachable angles),
– there is no collision between sensors and between sensors and digits,
– when grasping an object, all relevant sensors are in contact with the object.

The ranges of joints mobility of each finger (Table 1) due to the physical limitations of the hand kinematic structure and the influence of some finger poses on the free space remaining between them (the space where the sensors can be placed) have been tested using the TopSolid program.

Table 1. Motion ranges of the joints

Joint no.	0	1	2	3
Thumb	−10 100	−45 45	0 90	0 90
Fingers	−25 25	0 90	0 90	0 90 (coupled with joint 2)

Fig. 3. A configuration with maximum flexion of the fingers – tightening a fist and hook-type grasp of a mug handle

Figure 3 illustrates one of the tested configuration (maximum flexion of the fingers) strongly limiting the space for placement of the sensors. Following the simulations, shapes and permissible dimensions of the external sensors as well as their possible location on fingers were determined. The resulting design of sensors configuration is presented in Fig. 4. The shapes and sizes of sensors will be discussed in Sect. 3.

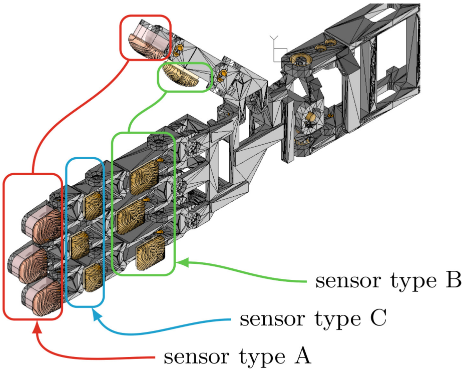


Fig. 4. Sensor shapes and placement

The designed final shapes and placement of sensors are a compromise between sensory system usability and versatility and an acceptable level of its complication. One of the most difficult grasp in respect of the study was the hook grasp of the mug handle. As shown in Fig. 2, only sensors of index, middle and partially thumb finger participate in detection of the contact with the object. This is sufficient to match the grip to the thickness of the mug handle, but only the placement of additional sensors on the sides of the phalanges could ensure the realization of this grip with full feedback.

2.3 Model of Grasping Process

Grasping with a human hand, based on premises presented in [17] and used in [18] may be seen as a 7-stage process. Those stages include: a_0 – rest position, a_1 – grasp preparation, a_2 – grasp closing (until a contact with object is detected), a_3 – grabbing (increasing contact forces until the values resulting from control command are reached), a_4 – maintaining the grasp with force adjustment, a_5 – releasing the grasp, a_6 – transition to the rest position. Possible flow of control between the stages is illustrated in Fig. 5.

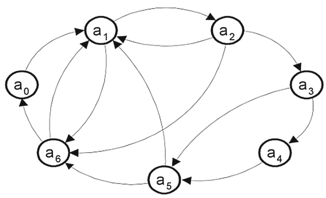


Fig. 5. Graph illustrating state flow of the grasping process

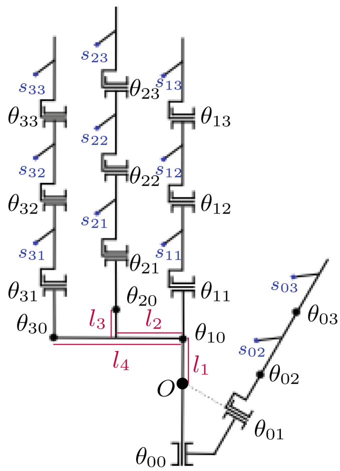
If a prosthesis controller includes an object geometry and receives a force feedback, the stages of the grasping may be formally described as follows. In the description for stage a_i following symbols will be used, with lower index $\cdot_F$ denoting a parameter for all fingers together and $\cdot_{Fjs}$ – for jth phalanx of finger s: $A_F(i)$ – real finger configuration, $A_F^{\max}$ – max degree of opening for the type of grip, $F^\star$ – desired contact force detected by sensor, $V_F(i)$ – finger velocity, and $F_{Fjs}(i)$ – measured (individual) force, $y^\star$ – recognized user's decision, $M(i)$ – measured grasp parameters, K – user's knowledge about grasped object, L – parameters of local control algorithms:

- a_0 – fingers move to the rest pose stored in the control algorithm ($A_F(0) \Leftarrow L$) and stay immobile and passive there ($V_F(0) = 0$, $F_F(0) = 0$),
- a_1 – type of grip is determined by the control decision based on user's recognized intentions ($y^\star \Leftarrow K$), the hand is opened to the maximum level suitable for the type of object to be grasped and motion velocity corresponds to the intended arm movement ($A_F(1) \Leftarrow A_F^{\max}(y^\star, L)$, $V_F(1) \Leftarrow M(1)$),
- a_2 – interactions of sensors with an object appear in any order, before the contact, motion velocity remains the same as in previous stage ($V_F(2) \Leftarrow M(1)$),
- a_3 – motion of each segment is stopped when a signal of touching the object is received ($F_{Fjs}(3) \neq 0$), the fingers increase the force applied to the object until the expected grasp force is reached ($F_{Fjs}(3) = F^\star \Leftarrow (y^\star, L, M(2))$)

a_4 – contact force in fingers is adjusted to maintain proper grasp ($F_{Fjs}(4) \Leftarrow M(4)$),
a_5 – the fingers are released with velocity depending on the knowledge about the object ($V_F(5) \Leftarrow K$),
a_6 – the fingers move to the rest position with constant velocity ($A_F(6) \Leftarrow A_F(0), V_F \Leftarrow L$).

2.4 Kinematics

The scheme of hand kinematics is presented in Fig. 6. Grasping an object requires a control of positions of several touch points on two or more digits at the same time. This assumption requires a definition of kinematics with multiple end-effectors. In a standard robotic approach, this type of kinematics is modelled as a tree-like manipulator using general formalisms like presented in [9,14]. But those methods are general, allowing all joints (both before branching and in all branches) to be actuated. In the case of the analyzed hand, formulas may be simplified due to the observation that all kinematic chains within the hand follow the same pattern: there is an initial branch in a palm, separating the digits, one or two-joint orientating a digit and a digit chain in form of a planar pendulum. The details of kinematic formulation of the hand without sensors was presented in [18], here we enhance the description to introduce multiple touch points.



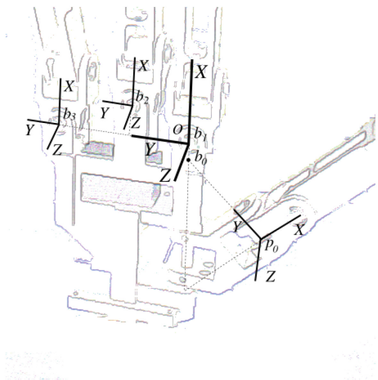


Fig. 6. Kinematic scheme and locations of the origins

The origin of the palm is denoted O and is placed in the center of rotation of the index finger. Digits of the hand are numbered from 0 in the following order: thumb, index, middle and ring finger. A vector of joint angles for a digit i will be denoted $\theta_i = (\theta_{i0}, \theta_{i1}, \theta_{i2}, \theta_{i3})$, where j is a joint number, starting from the joint connecting a digit to the palm, numbered 0. To describe transformations in a kinematic chain of a digit i, we distinguish the following special points in a kinematic chain of each digit:

- b_i is the base of the digit, i.e. the origin of the digit's coordinate frame,
- p_i is the origin of the planar part of the digit,
- s_i^j is a point on a sensor on phalanx j which is the origin of that sensor touch coordinate frame.

Coordinate frame of a contact point is represented as a homogeneous transformation $A_X^Y \in SE(3)$ between coordinate frames X and Y, composed of a 3×3 rotation matrix R_X^Y and a translation vector $t_X^Y \in \mathcal{R}^3$.

With the above notation, the description of each kinematic chain between the palm origin and a sensor touch point may be defined as

$$k_{s_i^j}(\theta_i) = A_O^{s_i^j}(\theta_i) = A_O^{b_i} A_{b_i}^{p_i}(\theta_i) A_{p_i}^{e_i^j}(\theta_i) A_{e_i^j}^{s_i^j}. \tag{1}$$

where the transformations from the palm origin to the base of the finger $A_O^{b_i}$ and from phalanx local frame to a touch point on that phalanx $A_{e_i^j}^{s_i^j}$ are constant. For fingers $A_O^{b_i}$ is built of identity rotation matrix $R_O^{b_i} = I_3$ and translations vectors $t_O^{b_1} = 0$, $t_O^{b_2} = [l_2 \; l_3 \; 0]^T$, $t_O^{b_3} = [0 \; l_4 \; 0]^T$. In the case of the thumb the transformation is given by

$$R_O^{b_0} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}, \qquad t_O^{b_0} = \begin{bmatrix} -l1 \\ 0 \\ 0 \end{bmatrix}$$

The constant transformation to the sensor in the phalanx frame is defined by

$$R_{e_i^j}^{s_i^j} = I_3 \qquad t_{e_i^j}^{s_i^j} = \left[-l_{ijx} \; l_{ijy} \; 0\right]^T.$$

The remaining two transformations of (1): between a digit base and its planar part $A_{b_i}^{p_i}$ and between the beginning of the planar part of a digit and the phalanx j – $A_{p_i}^{e_i^j}$ – are dependant on joint state vector θ_i. To define them, we use standard description with Denavit-Hartenberg parameters. The parameters for all digits are collected in Table 2.

3 Touch Sensor Construction

The touch sensors are built of three main elements: PCB, base case and a rubber pad (cf. Fig. 7). The layered build of the sensors has some flexibility allowing us to tune the base and pad thickness. Grasp analysis has led to a design of 3 types of sensor modules. Their locations and dimensions are summarized in Table 3.

The main element of the PCB is MPL115A2 – a pressure and temperature sensor. A number of PCBs that can be fitted in cases depends on the segment for

Table 2. Denavit-Hartenberg parameters

joint	thumb θ	d	a	α	
0	θ_{00}	0	0	$\frac{\pi}{4}$	b_0
1	θ_{01}	$-d_1$	L_1	$\frac{\pi}{2}$	
2	θ_{02}	0	L_2	0	p_0
3	θ_{03}	0	L_3	0	e_0^3

joint	fingers 1,2,3 θ	d	a	α	
0	θ_{i0}	0	L_0	$\frac{\pi}{2}$	b_i
1	θ_{i1}	0	L_1	0	p_i
2	θ_{i2}	0	L_2	0	
3	$\theta_{i3}{}^{\star}$	0	L_3	0	e_i^3

*finger joints 2 and 3 are coupled, therefore $\theta_{i3} = \theta_{i2}$, for $i = 1, 2, 3$.

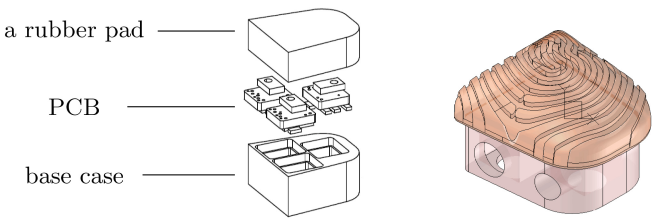


Fig. 7. Sensor elements

which the sensor is dedicated: from 1 for intermediate phalange up to 3 for distal phalanges (Table 3). Such a design may provide more precise information about direction and location of applied force. The base cases were 3D printed. The pad was made of soft (hardness 20 in Shore A scale) polymer rubber VytaFlex. The cast was prepared in vacuum degassing plant to remove remains of air between the pressure sensor and the rubber. Several tests with various shapes of the outer side of the pads has shown that ridged pads have superior grasp properties to those with smooth surfaces and for the best effect the ridges should be irregular, imitating fingerprints. Such shape allows a prosthesis hand not only to obtain a more stable grasp, but it will also allow detection of object slippage (we consider static objects which do not vibrate themselves) [6,16]. Location of sensors PCBs in the cases and the ready sensors are shown in Fig. 8.

The pressure sensors used in the design are factory calibrated for temperature changes and nonlinearity. However, the calibration parameters change after the sensor is covered with a rubber pad. Therefore before the modules can be used,

Table 3. Summary of sensor modules

Type	Phalanx		Dimensions l × w × h	No. of sensors
	Fingers	Thumb		
A	Distal	Distal	19.2 × 18.2 × 14.6	3
B	Proximal	Proximal	10.4 × 15 × 9.6	2
C	Intermediate	—	19.6 × 15 × 14.6	1

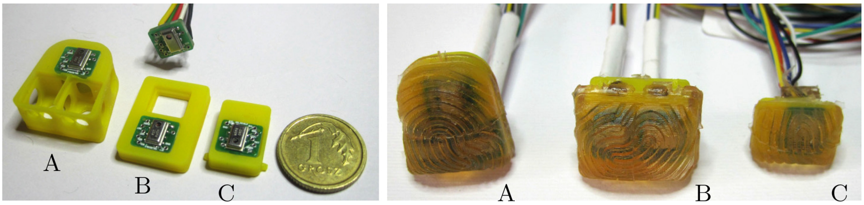


Fig. 8. Sensor elements: PCBs and cases (left) and ready sensors (right)

they have to be manually calibrated. The sensor used was heated with pressure and temperature measures, then a linear regression was used to calculate a correction $p = p_{raw} - (aT + b)$. The parameters determined for that sensor were $a = 29.522$, $b = 674.105$. However the process of covering the sensor with rubber is not standard, results for each module vary and each sensor requires separate calibration. Noise after calibration has not exceeded 1 % of the returned value. The calibrated sensor was tested with a load from 0 to 208 g. The readings are almost linear and the sensor detected loads as small as several grams.

The approach adopted assumes the installation of 4 sensor modules with 3 sensors, 3 – with 1 sensor and 4 – with 2 sensors, making a total of 23 sensors. The MPL115A2 sensor has a built-in address for I2C communication interface, therefore a support of 23 sensors require the 23 separate I2C lines. A possible solution is the use of the LTC4316 circuit to change the address of the MPL115A2 sensors for I2C communication interface. This enables direct communication of sensors with the main controller. Setting the address translation system LTC4316 is done using resistors; it be possible to set up to 127 different addresses.

The hardware solution used for communication between the sensors and the main controller enables readings with sensors maximum speed available to them (above 250 Hz). This allows the detection of pressure changes formed in sensors as a result of vibration accompanying the slip of rubber coating on the surface of the object being touched or held. This phenomenon is illustrated in Fig. 9. We see the 4 phases of the sensor operation. The phase 1 (between 7 and 8 s) - an increase in the measured pressure from 1250 hP to max 2000 hP, as a result of touch/shock of finger with object. Phase 2 (from 8 to 10 s), - maintaining pressure at 1800 hp, as a result of constant finger pressure on the object without slipping. Phase 3 (10 to 12 s) the pressure drop as a result of bending the finger rubber pad under the effect of transverse force, without moving. Phase 4 (12–17 s) - jumps/vibration of pressure by slipping of finger over the surface of the object. Phase 5 (17–18 s) - increase pressure to1700 hP, due to arrest the finger movement on the object surface.

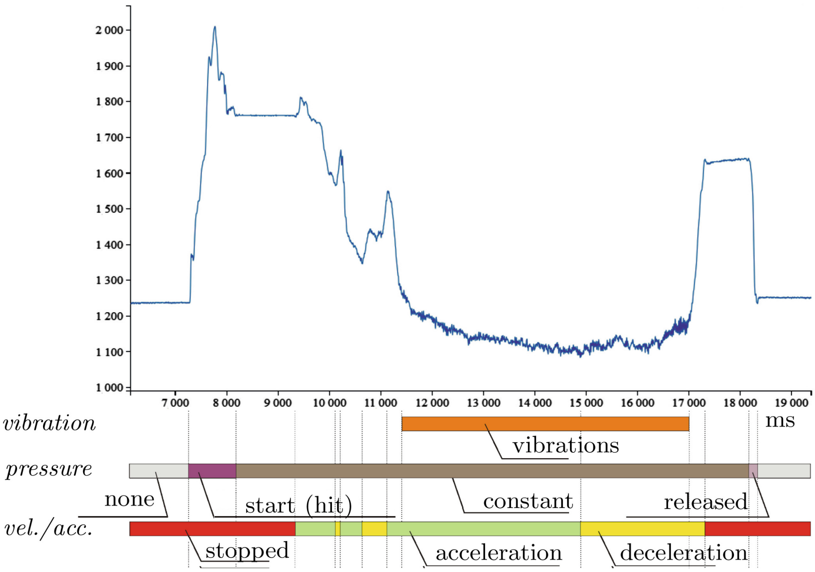


Fig. 9. Sensor response while slippage

4 Conclusion

Limited sensory systems of modern hand prostheses make their users replace touch feeling of a human hand with visual feedback by motion observation. Despite the richness of the information carried in vision channel, the lack of feeling of contact, pressure force or other impressions related to interaction between a prosthesis and a grasped object limits users capabilities of grasping. Comparing to vision systems, touch sensory systems are still not sophisticated enough, as there is no available technology capable of placing on an artificial hand a number of sensors comparable to the number of touch receptors in the human hand.

Despite those limitations, we proposed a solution that at least partially improves touch sensing of a prosthesis. A sensor designed for this purpose was tested and it proved to be capable of detecting and measuring contact forces during a grasp. The hand model was investigated for the best shapes and placement of the sensors to provide grasping capabilities focused on handling typical objects. Kinematics of the hand with sensors was modelled with simplified tree-like structures which can be further used in grasp planning algorithms.

Touch force information provided by the sensors may be used for designing new effective algorithms capable of dexterous grasping and manipulation with typical objects. An additional feature of the designed modules is capability of detecting a slippage of a grasped object. Further research will focus on how to use this information to adjust grasp force in grasp maintaining stage.

The idea of using fingers that are passive in a selected grasp to support an object requires some additional considerations. If the support is meant to be done automatically, the proposed sensors setup must be extended to detect force from a side of a finger. An alternative approach is direct control by the user, however it implies fine-grained intention recognition.

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