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Intrinsic tactile sensing system design for robotics manipulation

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***Abstract*— This paper presents an intrinsic tactile sensing system designed to be implemented in a robotic anthropomorphic finger, and to fulfill most of tactile sensing characteristics required to achieve dexterous manipulation of objects. The system consists of an array of four 3-axis force sensors linked to a rigid frame with a soft non-planar surface. The paper deals with the design, construction, mathematical modeling, calibration and testing of the system. The tests show high accuracy in the estimation of contact point and force components.**

***Index Terms*— Sensor, Tactile sensing, Intrinsic sensing, Force, Position, Multi-axial, Dexterous manipulation**

I. INTRODUCTION

The sense of touch is essential to objects manipulation. In the absence of a robotic tactile sensing theory [1], recreating this sense artificially is a big challenge. Most of the requirements and guidelines for designing tactile sensing systems needed to achieve dexterous manipulation of objects are based on the human hand characteristics [2] and contact theory [3]. The requirements can be stated as follows. The properties to be measured are: the normal and tangential forces, the torque perpendicular to the surface and the position of contact surface. The tactile system must be able to detect static and dynamic events, with a response time lower than $1\,\mathrm{ms}$. The spacial resolution of the system should be about $1-2\,\mathrm{mm}$ and have an elastic cover that increases the surface of contact. The system should have a force dynamic sensitivity of $0.01\,\mathrm{N}$ and a force range of $0.01 - 10\,\mathrm{N}$. Additionally, some suggested design guidelines are linearity in the measurements, magnetic shielding, robustness and high repeatability.

Tactile systems can be extrinsic, intrinsic or a combination of both. Extrinsic tactile systems measure directly the force applied on their surface. Commercial products could just measure the pressure distribution, but they can not measure tangential forces, nor the torque (example [4]). There are only few experimental extrinsic systems that have been developed to measure tangential forces like [5]. To respect the requirements, each sensor of the array must have a size of at most $2\,\mathrm{mm}$ by $2\,\mathrm{mm}$. As a result, the number of sensors may be large. This raises issues about the amount of information to process and makes this system difficult to implement.

Intrinsic tactile sensing is a method of estimating the contact forces, position and torques by measuring the forces (eventually torques) by a set of elementary sensors that are placed under the contact surface [6]. The advantage of this kind of systems is matching most of the required properties in tactile sensing, with a minimal quantity of sensors (starting at only one sensor). This type of sensing has been implemented multiple times. The implementation made in [7] is designed for manipulation of objects. This system uses a single 6-axis force/torque sensor. In [8], an array of 3-axis force sensors is used to create a haptic armor with multiple supporting points. In previous work [9], an intrinsic tactile sensing system was created using an array of three 3-axis MEMs force sensors. This system was a proof of concept created to verify if it could meet the proposed tactile system characteristics required to achieve dexterous manipulation of objects. The system showed good characteristics, but was not small enough to be placed in a robotic anthropomorphous distal phalanx. The touch surface was flat and rigid, and did not have an elastic cover.

In this paper, an improved miniaturized version of the system presented in [9] based on intrinsic tactile sensing is proposed. The system is composed of an array of four 3-axis force sensors linked to a rigid surface covered with elastic material. Adding an extra sensor while reducing the system size and using a non planar soft surface instead of a rigid one has multiple advantages. It makes it suitable for the integration in the anthropomorphous robotic end-effector presented in [10]. It enhances the resolution of the system through information redundancy. It increases its robustness thanks to adding an extra support. Thus, the system can support more force with a higher resolution. Finally, the soft material gives a better grasp quality.

The paper is organized as follows: Section II presents the measuring principle of intrinsic tactile sensing system. Section III is dedicated to the design, construction, modelling and calibration of a specific configuration of the tactile system. Section IV shows the system validation tests applied to the system, as well as the results. Finally, conclusions are drawn.

II. THEORY OF INTRINSIC TACTILE SENSING

The basis of this method of measurement was proposed by Bicchi [6] in 1990. It aims in resolving the location of contact centroid, the force at the interface, and the torque about the contact normals between two objects, by knowing the measurements of forces and torques at the support of the system. The proposed system uses a 6-axis force torque sensor attached to an object of known geometry. A version of this system was presented in [7].

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It is possible to create a system with the same characteristics by substituting the 6-axis force torque sensor by an array of 3-axis force sensors. A tactile system using this principle with a relatively large surface is shown in previous work [9].

The surface of contact is supported by one or more sensors. The interaction between an object and the surface creates a surface of contact Δ. In this surface, a distribution of tractions composed of tangential and normal forces is created. The tractions are assumed to be compressive which means that there is no attraction between the touch surface and the object. The distribution of tractions can be simplified as a force $\vec{p}$, a torque $\vec{q}$ that is perpendicular to the surface under the conditions of soft finger contact as shown in [6], the force and torque are applied in the centroid of the distribution of tractions $\vec{c}$ with respect to coordinate frame B. Figure 1 shows the principle of intrinsic measure.

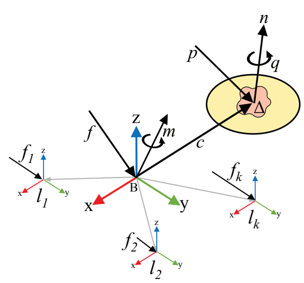


Fig. 1: Intrinsic measures

It is assumed that for dexterous manipulation of objects, the weight of the surface is negligible. For other implementations like a whole-body haptic sensing [8], the inertia of the surface should be taken into consideration. In a first instance, if there is only one support and it is placed in the origin of the frame B, the forces $\vec{f}$ and the torques $\vec{m}$ measured by the sensor are:

$$\vec{f} = \vec{p} \tag{1}$$

$$\vec{m} = \vec{q} + \vec{c} \times \vec{p} \tag{2}$$

Consequently, if the surface is attached to more than one support and those supports are placed in the positions l_i with respect to the frame B. The forces $\vec{f}$ and the torques $\vec{m}$ are distributed in the supports. Depending on the amount of supports, the needed sensors vary as shown in [9]. This paper deals with the case of a number k of supports (with $k \geq 3$). The following equations are derived:

$$\vec{f} = \sum_{i=1}^{k} \vec{f_i} \tag{3}$$

$$\vec{m} = \sum_{i=1}^{k} \vec{l_i} \times \vec{f_i} \tag{4}$$

Note that if all the vectors $\vec{l_i}$ in an arbitrary choice of the reference B are in the same direction, the equation 4 can not be solved. The surface is represented by the equation:

$$S(\vec{r}) = 0 \tag{5}$$

where S is the function that represents the surface, and $\vec{r}$ the vector that represents a point in space defined with respect to coordinate frame B, the surface S should have continuous first derivatives. As mentioned earlier, there are no adhesive forces. Thus the torque is proportional to the unit vector perpendicular to the surface:

$$\vec{n} \propto \vec{q} = \frac{K}{2} \nabla S(\vec{c}) \tag{6}$$

Where the vector normal to the surface is $\vec{n}$ and $K/2$ is a scale factor. The result of replacing the equations 1 and 6 in equation 2 is:

$$\vec{m} = \frac{K}{2} \nabla S(\vec{c}) + \vec{c} \times \vec{f} \tag{7}$$

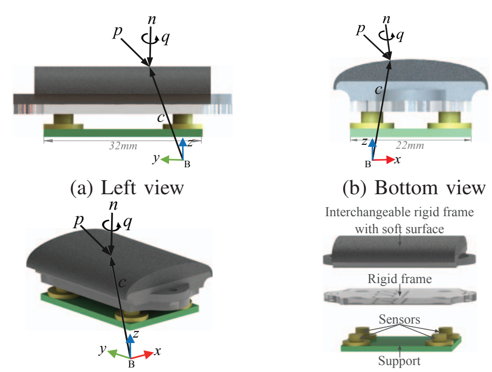
The system formed by the four non-linear equations 5, and 7, with four unknowns that are the position $\vec{c}$ and the constant K, can be solved as shown in [6]. The authors found two different ways to solve those equations in order to determine $\vec{p}$, $\vec{q}$ and $\vec{c}$ from $\vec{f}$, $\vec{m}$ and $S(\vec{r})$.

III. Tactile System

The system proposed in [9] satisfies many of the characteristics desired for tactile systems in dexterous manipulation of objects, as proposed in articles [1] and [2]. Some points, such as the elastic surface, non planar surface, or the size of the system are not accomplished. In this paper a new system more suitable for anthropomorphous robotics end-effector is designed. The system should be smaller, more robust and accurate than the one presented in [9].

A. Design of the system

The design of this system uses four 3-axis force sensors attached to a rigid frame. On this frame, different types of surfaces can be attached. In this work a rigid frame with a soft layer is attached as shown in the figure 2.



(a) Left view (b) Bottom view (c) General view (d) Exploded view

Fig. 2: Design of the system

This design has an extra sensor compared to the previous design [9]. By adding one more sensor, the forces and torques applied to the system are distributed on more supports, which increases the maximal force that can be applied to the system. Besides, adding another measurement, from the stochastic point of view, improves the estimation of the contact parameters.

B. Construction of the system

1) 3-axis force sensor and protection: The 3-axis force sensors used to build this system are based on MEMS (Micro Electro Mechanical System) technology. This sensors are developed by CEA-LETI as presented in [11]. Four sensors are attached and connected to a custom printed circuit board (PCB), as shown in figure 3a.

(a) PCB with four 3-axis force sensors

(b) PCB with four coated 3-axis force sensors

Fig. 3: Mounted sensors in the PCB

To protect the sensors and to increase the maximum supported force, each sensor is coated with a protection layer as shown in figure 3b. This coating is made by molding polyurethane directly on the sensors. The transducer function for each sensor is:

$$\vec{f_i} = \mathbf{S}_i \cdot (\vec{u_i} - \vec{b_i}) \tag{8}$$

Where the force vector measured by the sensor i is $\vec{f_i}$, the vector $\vec{b_i}$ (in V) is a voltage bias. The bias is specific to each sensor. The voltages $\vec{u_i}$ are the output voltages of the sensor. The matrix $\mathbf{S}_i$ (in $\mathrm{N\,V^{-1}}$) is the sensitivity matrix. These matrix are expressed in Newtons by Volts, transforms the voltage into force while taking into consideration the coupling effect caused mainly by the coating of the sensor. These matrix changes depending on the point of application of the forces on the coating. For this reason, it cannot be estimated before the rigid frame is glued.

2) Rigid frame and interchangeable frame: To ensure that all sensors are linked by the same rigid frame, and the forces are well distributed on all the sensors, the first rigid frame is glued to the coated sensors, as shown in figure 4a. And then, the interchangeable rigid frame with soft surface is fixed by screws to the first rigid frame as shown in figure 4b.

(a) First rigid frame

(b) Mounted tactile system

Fig. 4: Mounted rigid frame and tactile system

The first rigid frame is made with acrylic. The interchangeable surface is made by multi-material 3D printing, with the following characteristics: the rigid material that serves as frame has a tensile strength between 50 and $65\,\mathrm{MPa}$ and a shore hardness scale D between 83 and 86. The soft surface (the contact surface), has a tensile strength between 1 and $2\,\mathrm{MPa}$ and a shore hardness scale A 50. The equation of the contact surface S is expressed as an ellipse in the plane (x, z) (i.e. the x and z coordinates are dependent in an elliptic form and independent of the y coordinate). The surface is defined with respect to the reference frame B. To simplify the equations, the reference B is placed in the center of the ellipse in (x, z) plane and in the middle of the segment separating the two sensor couples along the y axis. Therefore, the function of the surface is expressed by the following equation:

$$S(\vec{c}) = \frac{c_x^2}{a^2} + \frac{c_z^2}{b^2} - 1 = 0 \tag{9}$$

where $a = 14\,\mathrm{mm}$ and $b = 5\,\mathrm{mm}$ are the semi-axes of the ellipse. The constraints of positions for $\vec{c}$ are:

$$-a \leqslant \quad c_x \quad \leqslant a \tag{10}$$
$$-16\,\mathrm{mm} \leqslant \quad c_y \quad \leqslant 16\,\mathrm{mm} \tag{11}$$
$$0 \leqslant \quad c_z \quad \leqslant b \tag{12}$$

C. Touch parameters estimation

The parameters that could be estimated with this system are: the contact position $\vec{c}$, the applied force $\vec{p}$, and applied torque $\vec{q}$. In this work, the test bench presented in section 5 has no means of generating or measuring torque. Since no torque reference nor torque generating system is available, the accuracy of torque estimation by the system is not guaranteed. Thus the applied torque value $\vec{q}$ is considered to be negligible in the following setup. Under these considerations, the model of contact used in this work is called point contact with friction, as explained in [3]. In fact, the presence of a reference torque measurement sensor would enhance the quality of system calibration and enables quantifying torque estimation accuracy. Future work will deal with torque estimation test using a high resolution reference force/torque measurement sensor. Substituting equation (3) in equation (1) gives:

$$\vec{p} = \sum_{i=1}^{4} \vec{f_i} \tag{13}$$

Consequently, replacing equation 13 and 4 in equation 2 and assuming that $\vec{q} = 0$, equation 2 becomes:

$$\sum_{i=1}^{4} \vec{l_i} \times \vec{f_i} = \vec{c} \times \sum_{i=1}^{4} \vec{f_i} \tag{14}$$

Along with equation 5, a system with four equations (14 and 5) and three unknowns (the position vector $\vec{c}$) is obtained. The system has two different solutions. These equations calculate the intersection of the axis formed by the force vector or wrench axis with the surface. This axis intersects the surface two times. The first intersection point corresponds to the force pointing towards the surface. The other intersection point corresponds to the force pointing away from the surface of contact. As mentioned in section II, the forces are assumed to be compressive which means that the object in contact with the surface can only push on the surface and can not pull the surface. By adding this constraint, the system has a unique solution. A method to solve this kind of problems was implemented in [6].

In our paper, the system is solved as follows. The value c_z is solved from equation (5). Given the limits in equation (12) the result is:

$$c_z = \frac{b\sqrt{a+c_x}\sqrt{a-c_x}}{a} \tag{15}$$

In the equation (14), the value of c_z is replaced by the result in (15).Then taking arbitrary two equations of 14, the values of c_x and c_y could be solved. Two possible solutions are found. Respecting the condition of compressive forces, a function that calculates the position $\vec{c}$ is:

$$\vec{c} = h(\vec{f_i}) \tag{16}$$

This function depends on the measured forces, the ellipse parameters a, b and the distances $\vec{l_i}$.

After neglecting the torque, the parameters to be estimated are the applied force $\vec{p}$ and the position of contact centroid $\vec{c}$. The input of the system are the voltages $\vec{u_i}$ measured by each sensor. By replacing equation (8) in equations (13) and (16), and joining those two equations, a non-linear model for estimating the touch parameters is constructed:

$$\begin{bmatrix}\vec{p}\\ \vec{c}\end{bmatrix} = g\left(\vec{u_1}-\vec{b_1}, \vec{u_2}-\vec{b_2}, \vec{u_3}-\vec{b_3}, \vec{u_4}-\vec{b_4}\right) \tag{17}$$

This model has, as input, the voltages $\vec{u_i}$ without bias $\vec{b_i}$ of each sensor and as outputs the applied force $\vec{p}$ and position $\vec{c}$. The model has as constants parameters: the surface constants a and b, the distances $\vec{l_i}$ and the sensitivity matrices $\mathbf{S}_i$. The values of the distances $\vec{l_i}$ are roughly known, and could be any point that is within the intersection between the coating and the rigid plate. The sensitivity matrix is unknown. The method to calibrate these parameter is shown in the next section. In this model the losses in forces made by the elastic material are supposed negligible.

D. Calibration method

To calibrate the touch system, the values of bias $\vec{b_i}$, sensitivity matrix $\mathbf{S}_i$ and the distances $\vec{l_i}$ must be estimated. Because the bias could change with the temperature (sensor piezo-resistive nature [11], or expansion/contraction of the rigid frame), the bias is calculated every time the system starts and do not have any force exerted. To estimate the rest of the values, a non linear mean squares minimization is used as follows:

$$\{l_i, \mathbf{S}_i\} = \underset{l_i, \mathbf{S}_i}{\operatorname{argmin}} \sum_{j=1}^{n} \left(\underset{j}{\mathrm{ref}} - g\left(\begin{bmatrix} \vec{u_1}-\vec{b_1} \\ \vec{u_2}-\vec{b_2} \\ \vec{u_3}-\vec{b_3} \\ \vec{u_4}-\vec{b_4} \end{bmatrix}_j \right) \right)^2 \tag{18}$$

where $i = 1, 2, 3, 4$ is the sensor index, ref is the reference measurement at sampling time j, n is the number of samples.

IV. Tactile System Validation

A. Experimental test bench

The experimental test bench used to calibrate and test the system is shown in the figure 5.

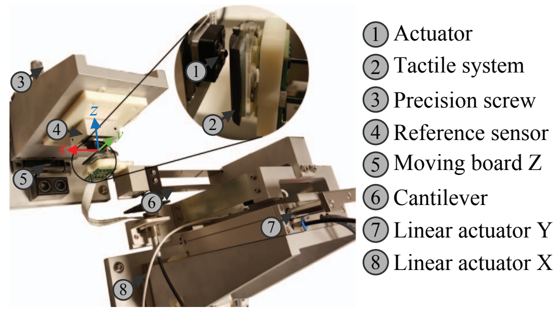


Fig. 5: Intrinsic measures

The system consists of two programmable linear actuators, which move as commanded in the x and y axis. These actuators are equipped with an optical ruler that controls the position with a $1\,\mu\mathrm{m}$ accuracy. A cantilever that functions as a spring in the z axis is assembled on the actuators. The developed tactile system is placed on the end of the cantilever, and the system is aligned with x and y axis of the system. A reference 3-axis force sensor (the K3D40) is assembled on a board, in front and parallel to the tactile system. This board can move in the z axis by a precision screw or by a pneumatic actuator. A metal sphere of $4\,\mathrm{mm}$ diameter is fixed on the end of the reference sensor. This shape helps to have the center of applied forces near to the center of the sphere. This setup was tuned in order to respect the following constraints: deformation of the cantilever or the coating of tactile system in the x and y axis are negligible. The reference sensor surface and the tactile system rigid surface are considered parallel all along the experiment. The calibration of the system is made by applying a wide range of forces on a extensive set of positions in order to explore most of the sensing dynamics. To meet this requirement, the following calibration process is proposed:

- The system is placed at the starting position of a predefined trajectory as shown in figure 6, and data acquisition is started.
- Precision screw is rotated until the actuator exceeds a force of $1\,\mathrm{N}$ in the z axis (this force is the minimum force applied during the test, the force changes according to the elevation of the surface). The reference of force is measured by the K3D40 sensor.
- The system is moved to follow multiple pre-defined trajectories as shown in the figure 6. The speed of the linear actuators during the displacement is $2.5\,\mathrm{mm\,s^{-1}}$.
- At the end of each trajectory, the acquisition stops.

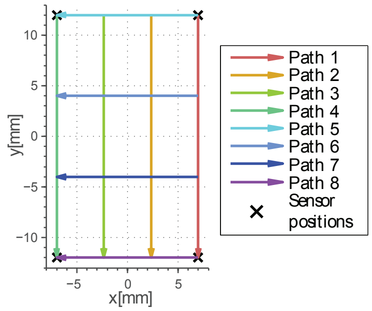


Fig. 6: Trajectories for calibration

All incoming signals are amplified using a custom made analogous amplifier. And then digitized by a data acquisition (DAQ) board PXI-6225 National instruments, at a frequency of $1\,\mathrm{kHz}$. The signals are also filtered with a second order low pass filter with a cut frequency of $100\,\mathrm{Hz}$.

B. Experimental results

For each trajectory presented in figure 6, two independent sets of measurements were prepared. The first set is used for the calibration of the system, and the second set is used for the verification. Using the first sets of measurements, the calibration method explained in section III-D is applied. The calibration is applied to the second sets of measurements and equation 17 is used to determinate the force $\vec{p}$ and the contact position $\vec{c}$. Errors compared to the reference system are then computed.

The minimal force that needs to be applied to accurately find the position depends on the resolution of the sensors as shown in [12]. In a future paper, an accuracy analysis will be made for this specific system. This analysis presents the details of calculating the theoretical minimal force required to achieve requested accuracy as well as the theoretical maximum error in position of $2\,\mathrm{mm}$ also known as spacial resolution of the tactile system, as proposed by [1]. For the current paper, the estimation of the position is made when the norm of the applied force is greater that $\|\vec{p}\| \geq 0.6\,\mathrm{N}$.

The results of this experiment are shown in the figure 7. The error statistics compared to the reference for all the verification measurements are show in table I.

Measure	Mean error	Max error	Standard deviation	RMSE
p_x	$1.2045\,\mathrm{mN}$	$158.0748\,\mathrm{mN}$	$29.2061\,\mathrm{mN}$	$29.2309\,\mathrm{mN}$
p_y	$-1.1449\,\mathrm{mN}$	$108.6501\,\mathrm{mN}$	$22.3881\,\mathrm{mN}$	$22.4174\,\mathrm{mN}$
p_z	$3.4771\,\mathrm{mN}$	$206.8778\,\mathrm{mN}$	$18.7274\,\mathrm{mN}$	$19.0474\,\mathrm{mN}$
$\vec{p}$	$37.7935\,\mathrm{mN}$	$240.5656\,\mathrm{mN}$	$17.0715\,\mathrm{mN}$	$41.4703\,\mathrm{mN}$
c_x	$-625.1968\,\mathrm{nm}$	$611.1280\,\mu\mathrm{m}$	$103.8326\,\mu\mathrm{m}$	$103.8344\,\mu\mathrm{m}$
c_y	$2.3156\,\mu\mathrm{m}$	$520.0804\,\mu\mathrm{m}$	$94.6500\,\mu\mathrm{m}$	$94.6783\,\mu\mathrm{m}$
c_z	$136.1755\,\mathrm{nm}$	$79.0515\,\mu\mathrm{m}$	$13.9571\,\mu\mathrm{m}$	$13.9578\,\mu\mathrm{m}$
$\vec{c}$	$118.6432\,\mu\mathrm{m}$	$621.0372\,\mu\mathrm{m}$	$76.5780\,\mu\mathrm{m}$	$141.2105\,\mu\mathrm{m}$

TABLE I: Error statistics for experiment 1

The force estimation, as shown in figures 7.a, 7.b, 7.c and in the table I shows a good matching with the reference. The noise of the estimated forces is significantly lower than the reference system. The measured standard deviation of the noise measured by the reference system in the absence of applied forces is $17\,\mathrm{mN}$. The proposed tactile system has a measurement noise of only $2\,\mathrm{mN}$. Consequently, the error is mostly dominated by the noise of the reference system (as seen in figures 7.3). In further work, a better reference sensor is going to be used (ATInano17). The position estimation (shown in figures 7.a) follows all the eight reference paths without offset. Table I presents the error statistics between estimated data and reference data. The repeatability of the results is tested with paths intersection positions, i.e. for different conditions in tangential forces, and different lapses in time, the sensor succeeds in having the same measurement in position.

V. Conclusions

This paper deals with the design, construction, mathematical modelling and calibration of an intrinsic tactile sensing system designed to be implemented in a robotic anthropomorphic end-effector, and to fulfill most of the requirements for dexterous manipulation of objects ([1], [2]):

- The measured properties : The three components of the force and the three components of the torque applied to the surface. As well as the position of the contact centroid.
- Sensing surface: Curved surface with soft cover.
- Spacial resolution: About $150\,\mu\mathrm{m}$ (for $1\,\mathrm{N}$ force).
- Sensitivity range: $10\,\mathrm{mN}$- $5\,\mathrm{N}$
- Dynamic resolution: $20\,\mathrm{mN}$ (Standard deviation)
- Response profile: Good stability and low hysteresis.

The design of the system consist of an array of four 3-axis force sensors linked to a rigid frame covered with a soft surface. The mathematical model is a special case of the model proposed in [6]. The calibration of the system is obtained by reducing the quadratic error between reference measurements and the estimated state of the mathematical model in order to find the unknown parameters of the system.

The tactile system can measure the three components of force, as well as contact position under the conditions of soft tactile sensing [6]. This system is also able to measure the three components of the torque applied perpendicular to the surface but the necessary equipment to validate and qualify the accuracy of torque estimation was not available as explained in section III-C.

This system is a considerable improvement compared to the system developed in previous work [9]. It has a non-planar soft surface. The base of the system is $22\,\mathrm{mm}$ wide by $32\,\mathrm{mm}$ long which is small enough to be implemented in the fingertips of the robotic manipulator presented in [10]. The system can estimate the applied forces and the position of contact with great accuracy. Here, the maximum measured error in force is $240.57\,\mathrm{mN}$ and the root mean square error (RMSE) is $41.47\,\mathrm{mN}$. The maximum measured error in position is $621.04\,\mu\mathrm{m}$ and the RMSE is $141.21\,\mu\mathrm{m}$. The force estimation error compared to the reference system is nearly the same as the one obtained using the previous system. In fact, this error is mainly dominated by the high noise level in the signals provided by the available reference system used in these experiments. A more accurate system with a

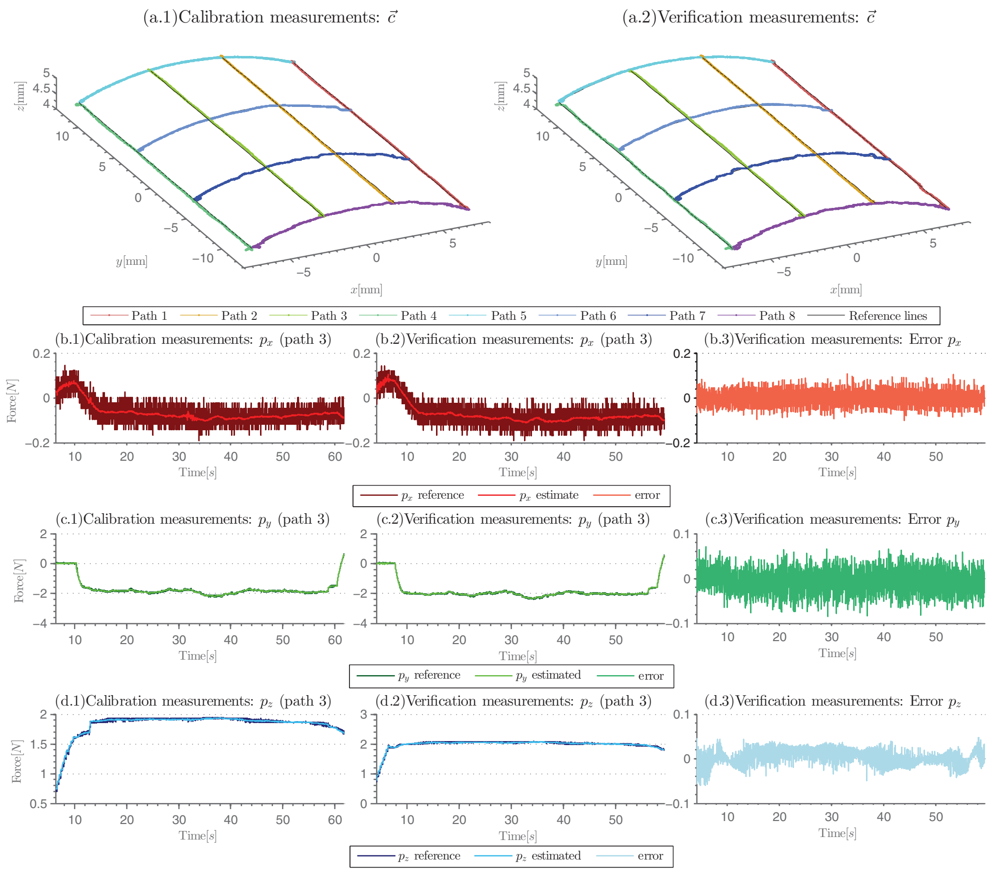


Fig. 7: Experimental results

significantly lower noise level will be used in further work in order to better qualify the designed system accuracy. On the other hand, the position estimation accuracy has been well enhanced using this system (provides a standard deviation of the position error of $76\,\mu\mathrm{m}$) compared to the previous one[9] (provides a standard deviation of the position error of $372\,\mu\mathrm{m}$.

This system matches almost every requirement proposed by [1], [2] for dexterous manipulation of objects with the exception of detecting the shape of the contact surface. Further work will try to implement multi-touch by creating a hybrid intrinsic/extrinsic sensor combining the presented system and an array of pressure sensors in the soft surface using extrinsic technology such as capacitive or resistive technology.

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