A Modular High-Speed Tactile Sensor for Human Manipulation Research

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Abstract
Tactile sensing is an important field of research in the domains of human-computer and human-robot interaction. To provide appropriate tactile sensing capabilities, this work presents the development of a new modular tactile sensor system focusing especially on high frame rates (up to 1.9 kHz) and good spatial resolution (5 mm). Larger sensor areas are composed from identical sensor modules providing a 16×16 matrix of tactels. We compare different tactile layouts and different force-sensitive materials to achieve optimal sensitivity especially to low forces in order to facilitate detection of first touch. An example application demonstrates the capability of the developed sensor to detect tiny variations in applied force.

Index Terms: B.4.1 [Hardware]: Input/Output and data communications—Data Communications Devices B.m [Hardware]: Miscellaneous—;

1 Introduction
The physical contact with the environment is a natural method for humans to influence and learn about the physical world. Measuring this tactile information provides insight on how humans perceive and employ tactile feedback and thus helps in generating better stimuli for haptic displays. Also, tactile information acquired from human-object interactions provides insight into the required complex control processes and thus provides the basis to endow robots with similar dexterous manipulation capabilities, e.g. to cautiously grasp fragile objects with minimal force while avoiding slippage.

Consequently, in the past decades tactile sensors were developed exploiting a variety of physical principles, namely piezoresistive, capacitive, quantum tunnel effect, optical, ultrasonic, magnetic, piezoelectric, pressure, etc. Cutkosky et al. review the working principle of most sensor types and discuss their advantages and disadvantages [2]. Dahiya et al. give a compact review of sensor types and derive requirements for robotic tactile sensors from considering the properties of the human prototype [3]. However, many available tactile sensors largely remain unsatisfactory either because they are too big, too stiff, too slow, or do not provide enough spatial resolution or sensitivity.

Harmon and Shindoa [5, 19] list features of the ideal tactile system: high spatial and temporal resolution, measurement of the force vector, high sensing range, versatile usage and skin like properties. Shinoda especially emphasizes the use of contact materials with properties (friction, elasticity) comparable to the human skin as a prerequisite for imitation of human tactile sensation. The sensor concept proposed in this work focuses on high spatial and temporal resolution as well as high sensitivity to first touch, as these properties are essential for autonomous robotic grasping and manipulation; e.g. we have previously shown [15] that the early detection of first contact proved important to avoid accidental pushing of an object prior to grasping. However, a major remaining problem in robotic manipulation is detection of incipient slippage and the adaptive control of grasp force.

Results from physiological experiments show, that humans can perceive incipient slippage of objects [9, 12], utilizing high-frequency micro-vibrations in the range of 65–400 Hz, which are amplified by the papillary ridges on the finger tips [16]. Appropriate tactile sensors, which exploit those vibrations for slip detection were developed [4, 7], but lack spatial resolution. On the other hand, high-resolution tactile sensor arrays only provide frame rates up to 100 Hz [22, 17]. Consequently, we aim for frame rates of 1kHz or more to afford detection of vibrations and high speed contacts, and to facilitate closed-loop robot control using tactile feedback.

The request for easy configuration and composition of larger sensor areas from multiple sensors as formulated in [5], is fulfilled by a modular, self-configuring sensor design employing a standard USB video interface for data transmission. Each sensor module (80×80mm) comprises an array of 16×16 tactels, thus providing a spatial resolution (5mm) similar to the human palm [1].

The remaining paper is organized as follows: In the next section, we describe the overall system architecture and the design decisions taken to achieve the targeted high frame rates. In the subsequent section 3, experiments are described to evaluate various electrode layouts and different conductive foams to improve the sensitivity of the sensor to low forces, which facilitates detection of first contact. An application scenario described in section 4 demonstrates the applicability of the developed sensor for object pose recognition from tactile information. Finally the results are summarized and further development lines are discussed in section 5.

2 Sensor System Architecture
2.1 Design Considerations
One of the major design decisions in developing our tactile sensor system was to follow a modular concept, where large sensor areas can be built from a composition of identical smaller sensor modules. This modular concept facilitates the use of the sensor system in various application scenarios having different requirements regarding the sensor layout and dimensions.

Consequently, a single sensor module, mounted to the end-effector of a standard robot arm, can act as a (large) tactile-sensitive fingertip, while the robot arm acts as a (large) finger. This setup allows to study autonomous grasping tasks mimicked from humans as well as active exploration tasks aiming at the reconstruction of the 3D shape of a touched object. At the other extreme, an arbitrarily large sensor area can be composed to cover a desktop, thus turning it into an “intelligent surface”. In this case, the sensor can passively record spatially-resolved force profiles of manual action sequences performed by a human, which can be subsequently analyzed to better understand and model human manipulation strategies.

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2.2 Sensor principle

Our sensors utilizes the resistive sensing principle, which is a popular method used in several previous tactile sensor developments. The method uses conductive elastomers, which change their resistivity in dependence of the applied load. Force-sensitive elastomers can be based on silicon, foams, or even cloth. Their conductivity is usually generated by graphite particles included in the material. To measure the resistivity a simple voltage divider is employed, whose pull up resistor can be used to adjust the sensor’s sensitivity.

We employ a single-sided contacting of the sensor material with an electrode array as proposed in [10], which exposes the other side of the elastomer directly as the contact area. To avoid spurious sensor readings occurring with row- and column-wise multiplexing of sensor readings, we decided to use a separate electrode for each tactel together with a common ground electrode. Although this increases the wiring effort tremendously, it guarantees clear measurement results. We explicitly avoided a single wire approach [13] to avoid problems arising from electrical noise from neighboring modules and other robotics components, considering the different application scenarios we aim for.

2.3 System layout

In order to have a scalable system composed of simple uniform modules we use a central unit, which acquires the sensor information from the modules and provides a standardized interface to a common PC. The modules are connected to the central unit through a proprietary parallel bus system as illustrated in Fig. 1. Aiming at frame rates of 1000 Hz for a single sensor module of 256 tactels and alternatively 100 Hz for a large sensor area comprising around 10,000 tactels calls for a raw data bandwidth for the transmission to the PC of 3 Mbps and 12 Mbps respectively, assuming a resolution of 12 Bit per sensor element. This rules out ordinary serial communication like RS232 (230 kbps) or CAN (1 Mbps). Instead an USB 2.0 High-speed connection was chosen, which offers enough bandwidth (480 Mbps) and is supported by all modern PCs, such that no special I/O hardware is required. As protocol the USB video format was chosen, such that the sensor data are transferred as image frames. This method allows to use standard device drivers available on all major operating systems. Additionally, the protocol can be used to transmit meta data, like the size and arrangement of the sensors.

To limit the wiring effort and to reduce environmental influences on the signal quality each sensor module acquires and digitizes its sensor readings locally, close to the electrodes, and only transmits digital data to the central unit. Because a single module comprises 256 tactels and the employed A/D converters provide 16 multiplexed input channels, we use 16 ADCs per module each covering a sub area of 4×4 tactels.

Because we could not fit all electronic components for data acquisition and communication onto a single PCB, each sensor module is composed from two PCBs stacked over each other. Figure 2 depicts a module and sensor surface together with the covering conductive foam. To connect several modules with each other, opposing pin headers and sockets are used, which incorporate power pins as well as the bus system pins for communication with the central unit.

Each unit employs a PIC32 micro controller unit (MCU) to acquire and store all sensor readings of the module. This offers the important advantage of parallel data acquisition: While one sensor module is transmitting its sensor image to the central unit (which forwards it to the PC), all other modules can independently collect their ADC data. Locally, an SPI bus is used for communication between the MCU and the ADCs. Capsuling the sensors and data acquisition into modules with these attached to a bus is similar to work of Ohmura et al. [14] and Hoshi et al. [6]. Both authors transmit the sensor data from node to node, as a conventional continuous MCU bus is too sensitive to noise over longer distances (>10ms). We use a similar technique by employing buffer chips to amplify the communication signals. There exist interesting methods of node communication via surface [20] or air [11] which do not require a physical connection between the nodes. However we found such methods not suitable for our task, as the modules need to have physical contact to form bigger sensor surfaces and these communication methods do not provide spatial information about the location of modules to facilitate composition of large sensor images. We have chosen a proprietary 12 Bit parallel bus instead of a standard serial bus for several reasons. First, a parallel bus can be operated at lower clockspeed (by a factor of 12), resulting in decreased emission and susceptibility to electrical noise. Second, we can exploit the explicit control of the pin levels to implement our autodiscovery algorithm described in secion 2.5 to identify the sensor layout. This eliminates the need for explicit modifications to the node connections or node software in order to match the actual sensor configuration, as it is necessary in other tactile array systems.

2.4 Achieving High Frame Rates

The most development effort was put into the design of efficient data acquisition and transmission to realize highest frame rates. The speed of the tactile system basically depends on two factors: the data acquisition time and the...
transmission time.

The limiting factor for the data acquisition phase is not – as expected – the raw sampling rate of the A/D converters (which is one million samples per second) but the time needed to charge the internal capacitor of the ADC to reach the actual sampling voltage after changing an ADC channel. This charging process has an exponential characteristic, where the decay factor is determined by the resistivity of the overall system, which is comparatively large (≈ 1 MΩ).

The time needed to reach a constant voltage level was identified in experiments to be approximately 30 μs, in comparison to a theoretical sampling time of only 1 μs.

To improve the overall acquisition speed, we thus alternately sample from each of the 16 ADCs on a sensor module before the next channel of the first ADC is sampled again. Using a sampling time of 1.2 μs to achieve more robust ADC readings, the time needed to acquire all 256 sensor values of a single module accounts to 308 μs, leaving a time of 15.1.2 μ s ≈ 18 μ s for voltage adaptation. This reduction of the adaptation period (compared to 30 μ s) is a trade off between speed and accuracy.

The data transmission to the host computer can be split into two stages: the transfer from the each module MCU to the central unit and further to the host PC. While the latter is extremely fast – requiring an average of only 32 μ s per sensor module due to the standardized High-speed USB connection implemented on the central unit – the transmission time from the MCUs to the central unit amounts to 333 μ s per module. Figure 3 summarizes these timing results in a concise diagram.

In the presence of multiple sensor modules, we follow a parallel data acquisition and transmission scheme as depicted in Fig. 4. While one module transmits its collected data to the central unit, the other modules acquire new data. Considering N modules the time to acquire and transmit a whole sensor image amounts to N · (333 μ s + 32 μ s), which results in a frame rate of N \( \cdot \) 1.2 kHz (N \( \geq \) 2), as illustrated in Fig. 5. Using a quadratic sensor area with edge length 480 mm, composed of 6 × 6 modules accumulating to an overall number of 9.216 tactels, this results in a frame rate of approx. 75 Hz.

To operate a single sensor module, where the described principle of parallel data acquisition and transmission cannot be applied, we use another optimization method: While acquiring the value for a tactel from the ADC, the value of the previously read tactel is already transmitted to the central unit. With this method it takes 494 μ s instead of 308 μ s + 333 μ s to acquire a whole sensor image, resulting in an overall frame rate of 1.9 kHz.

2.5 Identification of Sensor Layout

Having multiple sensor modules connected to form a larger sensor area, it is on the one hand important, that the central unit can discover the actual module layout in order to compose the overall sensor image from local module patches. On the other hand, a unique data transmission route has to be defined for communication with all modules to ensure robust communication.

Hence, on start up the central unit discovers all attached modules. This process is possible because the data signals of the parallel bus are transceived via buffer chips at each of the 4 connectors and these buffers are controlled by the
MCU on a module to one of three possible states: input, output or off. While every module alternately probes its four edge connectors, the central unit repeatedly sends a special module discovery signal. If the first connected module recognizes this signal on one of its connections, it acknowledges the signal, thus announcing its existence.

Subsequently the module tries to forward the bus communication to the next module in the chain by consecutively enabling the buffers at the edges and listening for an acknowledgement, whereby a time-out indicates that there is no connection. This procedure continues until all modules and their interconnection structure have been discovered. From the acquired information, the central unit derives a routing map and the layout of the sensor area and instructs the modules to adjust their buffer configurations to create a unique path of data flow. This method allows to identify all rectangular sensors layouts. The identified layout information is also transmitted to the PC as part of the USB video parameters, which allows the PC to reconstruct a large sensor image from separately transmitted module images.

3 Optimization of Force Sensitivity

In this section we discuss the results from several experiments to improve the sensitivity of the sensor to very low forces. We discuss two measurements to improve first-touch sensitivity: the electrode design and properties of the conductive foam.

3.1 Electrode Surface Optimization

The resistivity between the electrodes of a tactile sensor cell amounts to two components: the resistivity \( R_v \) of the sensor material between the electrodes and the surface sensitivity \( R_s \) at the transition from the electrode to the sensor material. As shown in theoretically substantiated experiments in [21] mainly the latter contributes to the load-dependent variation of resistance.

The variation of surface resistivity \( R_s \) is primarily generated by an increase of the actual contact area between the electrode and the sensor material: If a load is applied, the rough surface of the sensor material is pressed against the electrode, thus increasing the interface area as illustrated in Fig. 6. Consequently, in order to increase first-touch sensitivity, the distance between both electrodes should be reduced thus decreasing the material resistivity \( R_v \) which is proportional to the distance the current has to travel through the material.

Furthermore, an even more effective way to increase sensitivity would be to take advantage of single bulge contacts: Normally two contact areas are needed to yield a current flow between both electrodes. However, if a bulge of the sensor material is located directly above the gap between the inner and outer electrode it can simultaneously contact both electrodes when pushed down. To increase the probability of such contacts, we increased the circumference of the gap between both electrodes.

We evaluated different sensor shapes as shown in Fig. 7. For each of these shapes we considered several variations regarding the width of the electrodes themselves as well as the gap between them. The parameters of all tested shapes are summarized in Table 1.

![Figure 7: Quadratic sensor shape, M shape and star shape.](image)

Figure 6: Working principle of a resistive tactile sensor: An applied load increases the contact area between the sensor material and the electrode, thus decreasing the surface resistivity \( R_s \) (adapted from [21]).
Sensor output \([\%]\)

**D**

**e**

**r**

**n**

**c**

**r**

**o**

**m**

**a**

**r**

**e**

**s**

**u**

**p**

**u**

**t**

\([\%]\)

**S**

**e**

**n**

**s**

**o**

**r**

**o**

**u**

**p**

\([\%]\)

55

60

65

70

70

55

0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8

0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8

Average electrode distance [mm]

Figure 8: Sensor output of various electrode design in relation to the average distance between both electrodes, when a fixed load is applied. Sensitivity increases with decreasing average electrode distance.

**Average electrode distance [mm]**

**Sensor output [\%]**

Figure 9: Comparison of the sensor output for quadratic and M shape with different elastomers and increasing overall load ranging up to 30 kPa.

**Average electrode distance [mm]**

**Sensor output [\%]**

**[kpA]**

**Sensor output [\%]**

**[kpA]**

**Difference from average [\%]**

**WR**

**PU**

Figure 10: Comparison of interlocation and intralocation variance. The sensor was probed 100 times at 10 different locations with WR (Weiss Robotics) and PU (Polyurethane) foam. Each point shows the difference between the average output of the locations, while the errorbars show the range of different outputs at the specific location.

ing the same measurement setup as in the previous section we probed each of the sensor foams at 10 different locations with a fixed force of 5 kPa and 100 trials each. The results depicted in Fig. 10 show that the interlocation variance is bigger than the intralocation variance for both foams. We suppose this interlocation variance is due to different carbon levels or the bubble structure of the foam at different locations. The variance for the WR foam turns out to be lower. While the WR foam’s surface structure is smooth having closed bubbles in millimeter range, the PU foam has a highly porous surface. This leads to the conclusion that a more homogeneous foam surface ensures more robust sensor readings.

To quantify the sensors behaviour with different pressure levels, we measured the sensor output at increasing levels of pressure load. To reduce variance, we applied the load to the whole sensor area to remove the effect of the inhomogenous foam structure by averaging the output of all 256 sensor cells. Figure 9 shows the resulting output curves of the two different foams. Additionally we tested each foam with the square and M shape sensor type to verify the higher sensitivity of the M shape with different load and materials. The WR and PU foam show distinct pressure curves, with the PU foam having a strong response at light load below 0.5 kPa and reaching about 80% of maximum sensor output at 2.5 kPa. The WR foam is not as sensitive and reaches the same sensor output at 10-15 kPa. Nevertheless, the PU foam already saturates at a load of 15 kPa, while the WR foam covers much more range up to 30 kPa. Hence both materials are suited for different applications: either to detect initial contact or to measure contact forces over a large range of pressure. Comparing the impact of the different sensor shapes, it can be seen that the M-shaped layout shows slightly higher sensitivity for the PU foam and a noticeably increase with the WR foam. An explanation for this effect might be that the finer bubble structure of the WR foam matches with the smaller average electrode distance structure of the M-shaped design to create more direct bridge contacts.

4 Example Application: Estimation of Object Pose

To demonstrate the high sensitivity of the sensor system, we implemented a method to predict the rotation of a cup handle from the tactile profile generated by the cup placed on the sensor. Besides the detection of the object’s “tactile footprint” or shape and its position, this sample application makes use of the pressure intensity information. The color-encoded tactile image of the cup is shown in the bottom right of Figure 11. To detect the circular shape of the cup a hough transformation [8] is applied to the sensor image, thus determining the cup’s size and position. Using this information the center of gravity of all tactels within the circular cup region is calculated. As the handle of the cup adds more weight onto a particular side, the center of gravity differs from the geometrical center of the circular shape. Hence, the difference vector determines the orientation of the cup’s handle. The length of this vector can be used as a confidence value for the prediction. To evaluate the performance of the proposed algorithm, we tested three different cups listed in Table 2 and pictured in Fig. 11. For each cup the prediction error was averaged from five measurements obtained at eight orientations equally distributed around a circle.
Table 2: Prediction results for handle orientation of different cups

<table>
<thead>
<tr>
<th></th>
<th>diameter</th>
<th>weight</th>
<th>prediction error</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cup A</td>
<td>7 cm</td>
<td>265 g</td>
<td>16.8°</td>
<td>9.0°</td>
</tr>
<tr>
<td>Cup B</td>
<td>8 cm</td>
<td>342 g</td>
<td>13.5°</td>
<td>5.4°</td>
</tr>
<tr>
<td>Cup C</td>
<td>6 cm</td>
<td>520 g</td>
<td>10.2°</td>
<td>4.5°</td>
</tr>
</tbody>
</table>

The heaviest cup gives the best prediction results due to a better signal-to-noise ratio.

5 Summary and Outlook

We presented a tactile sensor system that is fast, offers a good resolution and sensitivity while being modular and easy to use. We commented on our choice of electronic components, hard- and software implementation as well as architecture design to achieve the targeted high frame rate of 1.9 kHz for a 16×16 array of tactels of a single module. Thus, our sensor is a magnitude faster than available sensors with similar configuration. Furthermore the sensor area can be gradually increased, which still results in a real-time frame rate of approx. 70Hz at 10,000 tactels.

The properties of two types of sensor foam were analyzed and the shape of the sensor electrodes was optimized to improve sensitivity to first touch. We presented a small application to demonstrate the high sensitivity of the sensor. The application of the sensor for incipient slippage – our initial motivation – was successfully demonstrated in [18], but is out of scope of the present paper.

We also have shown, that the sensor can be used to recognize various materials by analysis of the Fourier spectrum obtained from scrubbing over their surfaces [18].

The existing system provides a good basis for a broad range of interesting future research in robotics. These include the study of human object manipulation, to gain a better understanding about how humans coordinate their finger actions and forces. For such experiments the high speed of the system is advantageous as crucial parts of human actions happen in a range of milliseconds (e.g. grasping a falling object). The ability of the system to cover big sensor areas (e.g. using 36 modules to cover a 480×480 mm area) makes it also suitable for recording interaction processes that require more space, for example kneading clay or folding a paper on a desk.

References


