Proc. Int. Conf. on Robotics and Automation (ICRA) IEEE 1997

A Tactile Sensor System for a Three-Fingered Robot Manipulator

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Abstract: Tactile sensor systems are an essential prerequisite for the implementation of complex manipulation and exploration tasks using robots. Tactile exploration has not yet found its way into many laboratories, because most tactile sensors are technically demanding and expensive.

The desire to perform real-time control and pattern recognition with tactile sensors led us to the design of a cost-effective artificial fingertip. At our laboratory two distinct types of sensors are in use: force/position sensors, and slippage detectors. We report on first experimental results with a fingertip prototype performing rolling and sliding movements over a flat surface.

To facilitate experimentation with tactile sensors, we designed and developed a data acquisition and transportation system that fulfils our demands on bandwidth, flexibility, and cost. This system consists of two hardware components, a configurable multi-channel analog signal sampler (MASS) to acquire sensor data, and an intelligent dual-ported random-access buffer (BRAD) to avoid data transportation bottlenecks.

1 Design goals

In the past years manipulation with tactile sensors has evolved into a major interest in robotics research. Force-controlled grasping has been achieved using a variety of feedback devices [1, 2], of which many are inspired by the physiology of human skin [3, 4]. By understanding the smart and efficient methods we use when manipulating even the most fragile objects, better algorithms for robot manipulation may emerge.

Two classes of problems seem to predominate in this area of research: *(i) real-time force control* to enable a robot to manipulate fragile objects, and *(ii) tactile exploration* to gain texture, material and shape information that is difficult to obtain by other means, like computer vision. Both of these research goals share the need for sensory input either indirectly, e.g. from joint strain gauges, or directly, e.g. from tactile sensors at the fingertips.

In this paper, we present a fingertip prototype especially designed to suit the geometry and kinematics of the TUM robot hand developed by F. Pfeiffer et al. at the Technical University of Munich [5]. In our prototype, tactile sensors are stacked in layers to perform simultaneous measurement of contact force and position, and slippage detection. The sensor concept itself is applicable to robot hands in general.

For easy availability of sensor data, the sensor system is embedded into a versatile experimentation platform consisting of two hardware components, MASS and BRAD [6], which handle sensor sampling and data buffering respectively. These devices make the data available at a central VME bus with as little time delay as possible. This integration system is described in detail in the third section.

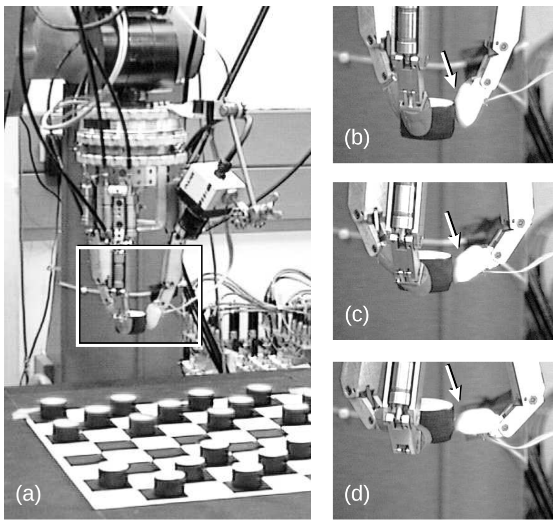

Fig. 1: **Hydraulic hand mounted on robot arm:** A typical sequence is shown where force sensing is needed while rolling over the contact surface **(b–d)**. The fingers have human-like degrees of freedom: a cardanic base joint for sideward and inward bending and two coupled joints for flexing.

The setup can be very flexibly reconfigured to allow the inclusion of different sensor types and provides us with a versatile basis to experiment easily with innovative sensor concepts.

Software interfacing of this system with other sensors and actors is performed using a SORMA [7] service object, which supplies clients throughout the network with sensory data.

Fig. 1 shows our robot manipulator in a typical setting [8]. The lower part consists of the TUM hand with three anthropomorphic fingers driven by an oil hydraulics system, each with three degrees of freedom. An additional wrist-mounted force/torque sensor (FTS) developed by Hirzinger et al. at DLR [9] provides information on the net force and torque exerted by the manipulator (including any objects being held).

A camera mounted at the wrist, as seen in fig. 1, can be used for planning grasp movements, but as soon as a contact with an object is established, the visual information alone is no longer sufficient and we need to perform force control.

Although the hand's oil hydraulics system allows fast and powerful movement control, it does not deliver reliable joint angles, because of hysteresis effects which cannot be compensated by measurements at the hydraulics system. By adding tactile sensors to provide accurate and reliable feedback on the contact state we mean to fill this information gap.

A single FTS cannot fill this need because of a physical restriction imposed by its principle of operation. An FTS can only produce reliable data for force control if either the location and shape of the contact is known, or if there is only a single hard contact point at an unknown location on a convex surface. In the latter case, the location of the contact point can be inferred from the manipulator geometry because the force vector is perpendicular to the contact surface. In the former case, tangential forces can also be applied, and therefore the contact location cannot be calculated.

Tactile sensors provide better information about the contact state in two ways: *(i)* More *detail* since multiple contact points can be localized, which is impossible with a single FTS, and *(ii)* more *sensitivity* through a sensor placement that is close to the contact. Since the FTS is subject to vibration noise and cable elasticity bias, this yields a better signal-to-noise ratio for small forces.

FTS's mounted inside fingertips [10] are very demanding from an engineering point of view. They trade mechanical stability with sensitivity, and share the restriction stated above of locating the contact surface when elastic coating is used. Therefore, we wanted to use direct contact sensors in a skin-like construction instead.

Since no tactile sensors suitable for our laboratory setup are commercially available, we decided to design a fingertip that is both sensitive and robust, which we will describe in the next section. This fingertip is simple and cost-effective in its design, so that several copies can be manufactured with little added expense. This also allows us to experiment with variations of the design and gather data on different concepts, e.g. sensory equipment for whole-hand manipulation.

2 A fingertip prototype

Our tactile sensor makes use of two types of polymer transducers to achieve simultaneous force/position sensing (using a piezoresistive semiconductor film called FSR^{TM} [11]) and slippage detection (using piezoelectric PVF_2 material [12]). Both sensor materials have already been used successfully in the area of tactile sensing [1, 13] (*FSR* applications in hand prostheses and in a robotic hand) [14, 15] (PVF_2 applications in dynamic sensing and in friction estimation).

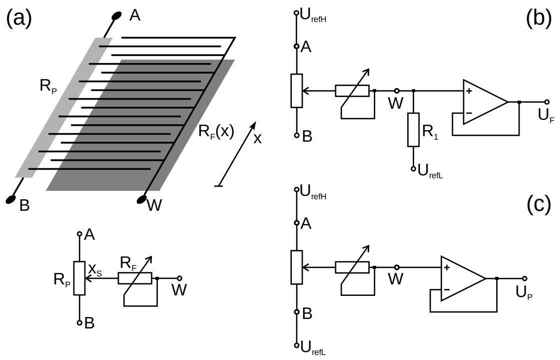

Fig. 2: **Principle of *FPSR* with amplifier circuitry:** The sensor consists of a set of interleaved electrodes **(a)** covered with force sensitive foil. The electrodes divide the foil into several fi elds (typically 10 to 20) that can be used for position sensing along one direction by applying reference voltages to A and B **(c)**. Integral force sensing can be achieved with the circuit **(b)**. To perform both measurements with one circuit, two switches are needed.

The sensor built with the piezoresistive foil is shown in fig. 2 along with the amplifier circuitry necessary to measure the applied force and the approximate position of the center of mass. To extract position information, one set of electrodes is connected to a small resistor R_P. Tying the outer electrodes A and B to fixed reference voltages results in a voltage level at W that reflects the weighted sum of the conductances $R_F^{-1}(x)$ along the x direction.

The piezoelectrical foil sensor is best compared to a capacitive microphone. Electrodes printed onto

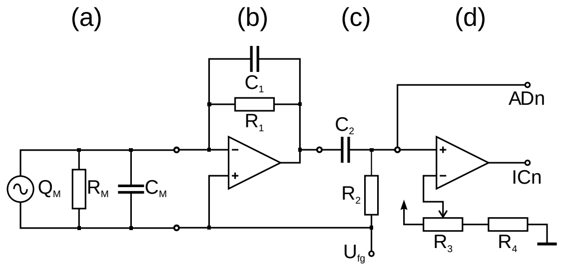

Fig. 3: **Amplifier circuit for one PVF_2 sensor:** The equivalent circuit for the sensor **(a)** shows the similarity to a capacitive microphone. A charge amplifier **(b)** and a first-order high-pass filter **(c)** produce the analog signal. The pulses generated by the threshold comparator **(d)** are subsequently analyzed by an edge detector.

both sides of the foil form a capacitor with a parallel resistor, see fig. 3 **(a)**. In the amplifier circuit, Q_M represents the charge generation due to deformations of the piezoelectrical material. The charge building up on the foil is immediately absorbed by a charge amplifier to reduce noise (fig. 3 **(b)**). The interesting frequency range is extracted with a high-pass filter **(c)** and the resulting signal is passed through a thresholding device **(d)** connected to an edge detector. This detector registers pulses down to 1 μs in duration.

The pulse train delivered by the PVF_2 sensor complements the readout from the piezoresistive device described above with information on small, fast changes of the contact state.

To achieve this, we arrange the two types of sensors in layers, as shown in fig. 4. A sheet of piezoelectric PVF_2 material forms the upper layer and is bonded to a knobbed rubber skin to detect vibrations during incipient slippage (i.e. when a knob at the boundary of the contact surface loses contact [14]). The piezoresistive material forms the lower layer and detects the applied force transmitted by the elastic padding.

Since the knobs produce pulses of a distinct shape (typically in a frequency range of 1. .10 kHz), high-pass filtering and thresholding of the dynamic sensor signal results in an effective slippage detector.

The mechanical design of the fingertip itself is shown in fig. 5. A polyhedral aluminum carrier **(a)** is used to mount four planar force/position sensors **(b)**, each consisting of a specially designed printed circuit board that carries the electrodes, and the piezoresistive polymer film. An elastic coating **(c)** and the knobbed rubber membrane with the dynamic sensor **(d)** are added. The shape of the polyhedron is designed to match the degrees of freedom of the

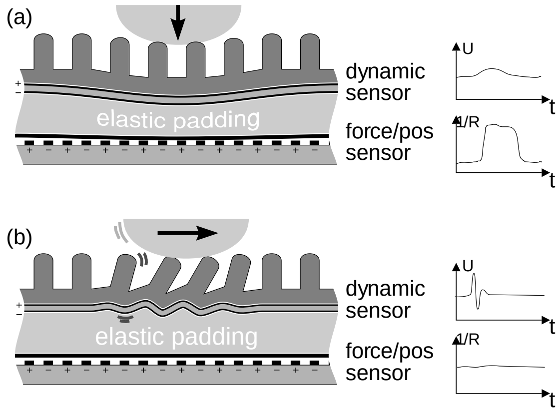

Fig. 4: **Principle of simultaneous force/position and slippage detection:** The combination of a PVF_2 sensor (upper layer) with a “tonic” piezoresistive sensor material (lower layer) allows reliable discrimination between static pressure **(a)** and slippage **(b)**.

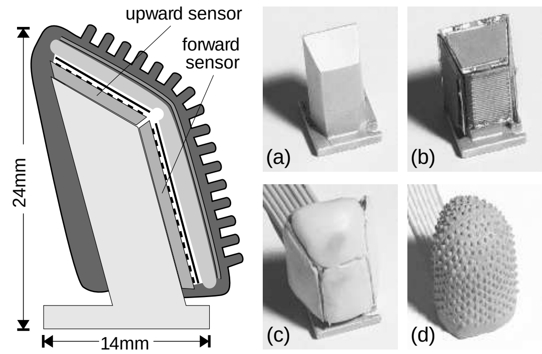

Fig. 5: **Mechanical design of the fingertip:** The photos show intermediate phases in the construction of a tip.

robot fingers, i.e. ideally, only one sensor should react to a change in the force applied by one joint angle. This simplifies the implementation of force control.

Fig. 7 shows the behaviour of a force sensor built into the prototype. Its sensitivity threshold is shown in the figure, along with a fitting function used to translate A/D units into Newton.

The elastomer coating with gaps along the edges of the polyhedron helps to avoid “blind spots” by transmitting forces acting on an edge to the two adjacent sensors. This is especially important since the fingertip is meant for manipulation tasks and therefore must not deliver unreliable contact state information depending on the configuration. Fig. 6 illustrates the force/position sensor behaviour during a rolling movement similar to the sequence depicted in fig. 1 **(b–d)**. The force measurement shows

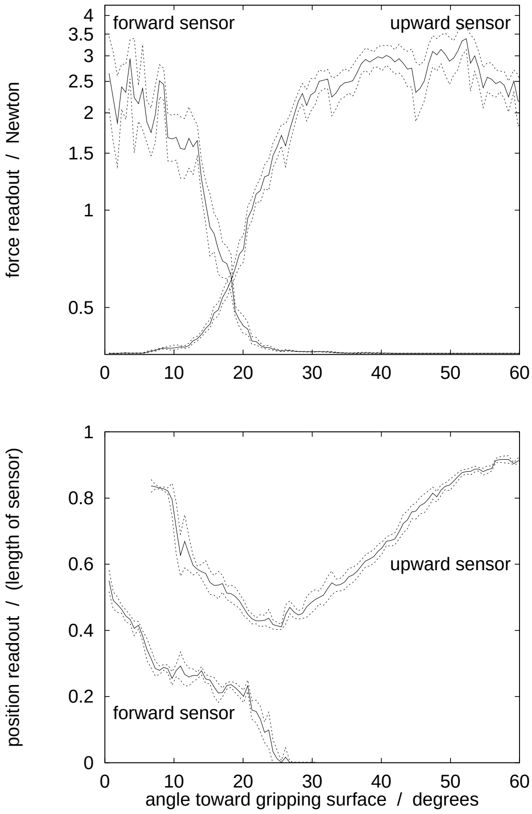

Fig. 6: **Simultaneous force and position traces of two sensors during a rolling movement:** Angles of 0° and 45° correspond to a parallel alignment of the contact surface with the forward and the upward sensor, respectively. When rolling over the polyhedron's edge, the upward sensor smoothly takes over from the forward sensor to produce reliable output throughout the whole movement.

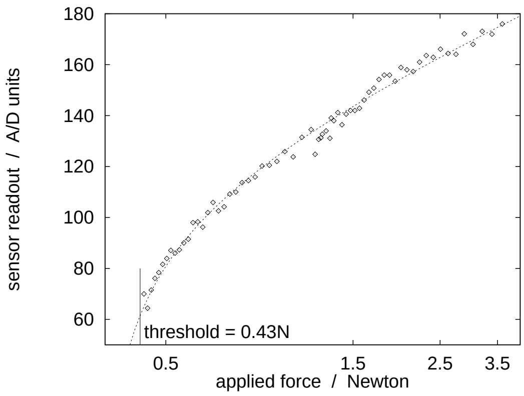

Fig. 7: **Typical trace of sensor readout vs. applied force:** The force sensitivity of the sensor is limited by a threshold that depends on the size of the gap between the foil and electrodes when no force is applied.

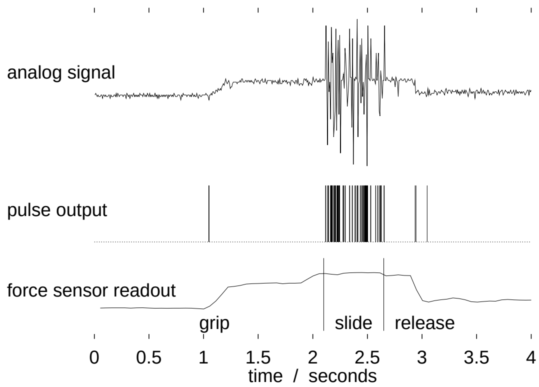

Fig. 8: **Slippage measurement during a sliding movement:** The robot arm pushes the fingertip onto a flat surface, slides, and then releases the grip. The edge detector warns if the analog slippage signal rises above a predefined threshold. Due to the low sampling rate, not all spikes are visible in the analog signal plot.

a smooth transition from the forward to the upward sensor. The noise level of the combined force and position signal appears very low in view of the considerable motor vibrations that superimpose the rolling movement.

Fig. 8 shows the time record of a typical sliding motion demonstrating the operation of the slippage sensor. The analog dynamic sensor signal is sampled with 2.3 kHz. Most spikes during a sliding motion can be seen in this plot, but very narrow spikes cannot be detected at this sampling rate. A fast edge detector provides more reliable information by releasing a warning pulse every time the analog signal rises above a given threshold (see fig. 3). With this method, slippage detection can be achieved even when using low sampling rates (about 500 Hz).

However, with this simple detection scheme, the detector is not strictly selective for slippage only, since intense membrane vibrations also occur due to environmental contact in other areas of the manipulator or when gripping and releasing an object. Fig. 8 shows some edge detector warning pulses in areas that correspond to these movements. The stray pulses are very likely to be separable from slippage pulses by using the simultaneous measurement of the contact force, e.g. its rate of change.

Apart from slippage detection, the dynamic sensor may also prove useful for more general tasks, like probing different surface features in tactile exploration.

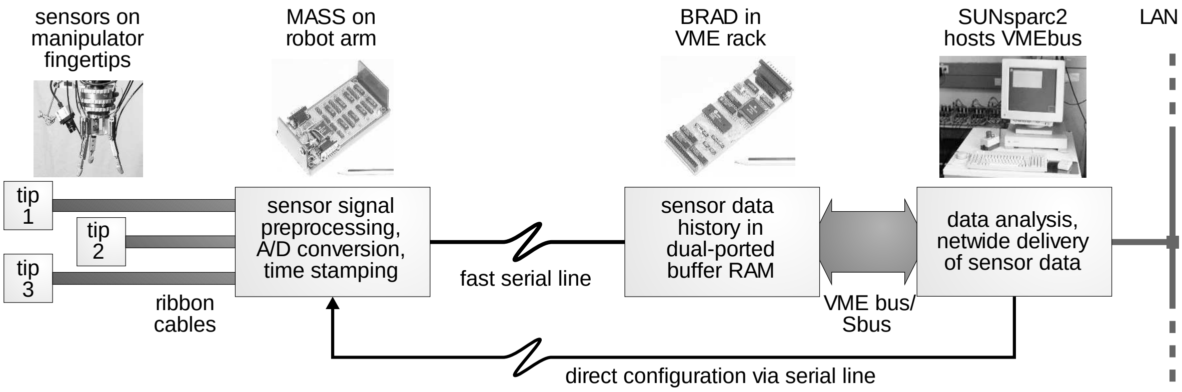

Fig. 9: **Diagram of the experimentation system:** Two components developed at our laboratory, MASS and BRAD, link the fi ngertip sensors to a standard workstation. MASS handles sensor sampling while BRAD ensures fast data transfer by means of dual-ported memory.

3 A modular sensor integration system

Data acquisition and transportation is an extremely important issue when designing an experimentation platform for tactile exploration. Some general design issues that have to be taken into account to build a useful sensory experimentation environment have been discussed by Jacobsen et al. [16]. Our main interest was the integration of the tactile sensor system into the current hardware setting with minimum interference. In an attempt to optimize cabling, bandwidth, reliability and flexibility the experimentation system sketched in fig. 9 was developed.

All analog signal preprocessing is carried out as close to the robot hand as possible by MASS (*Multi-channel Analog Signal Sampler*). Each finger requires eight wires (six for force/position measurement, two for slippage detection), which are bundled in ribbons about 25 cm long. After A/D (analog to digital) conversion the data are transmitted via a long 1 MBaud serial line to a buffering module (BRAD, *Buffered Random Access Driver*). This module is connected to a standard workstation, where data post-processing can take place.

The data acquisition device consists of an analog circuit for signal preprocessing, an A/D converter and a digital circuit for bundling, time-stamping and transmitting the data (see fig. 10).

The analog circuits are implemented as a separate piggyback module plugged into the main MASS board. With the fingertip prototype a module is used which contains amplifiers for up to 32 force/position sensors, and filters and thresholding devices for up to 4 dynamic slippage sensors. This leaves more

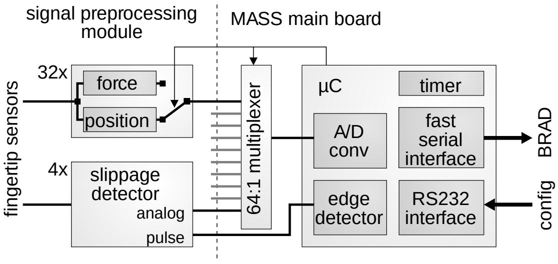

Fig. 10: **Diagram of MASS (*Multi-channel Analog Signal Sampler*):** The microcontroller gathers data from the sensors according to a confi gurable scan list and sends this data to BRAD via a fast serial line.

than 20 channels free for other uses. Additional modules for different types of sensors can easily be constructed.

The main board of the sampler consists of a multiplexer bank with 64 inputs and one output, and a microcontroller containing all other relevant devices: four edge detectors, the A/D converter, a timer, and two serial interfaces. The controller chooses the multiplexer channel and configures the signal preprocessing circuitry, e.g. by selecting force or position readout on one sensor.

A scan list in the controller's memory defines the sequence of channels to be sampled in one sweep. This list can be configured at any time by software via a standard RS-232 interface. During one sweep, the data are sent immediately after the A/D conversion to minimize the total latency time.

To aid controlling data integrity and monitoring the sampling rate, the data are organized in packets, one per sweep, that contain a time stamp and the delay between successive packets in units of 8 μs.

The buffering module BRAD receives these pack-

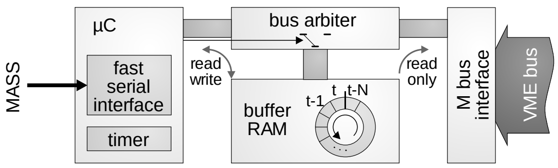

Fig. 11: **Diagram of BRAD (*Buffered Random Access Driver*):** The microcontroller receives data packets from MASS and maintains a ringlike history buffer. This buffer can be accessed at random from all VME busmaster devices.

ets and writes them into a history buffer that can be read out asynchronously by the workstation or any other VME busmaster.

The diagram in fig. 11 shows the main components of the device. The microcontroller writes the data coming in through the serial line into a RAM buffer. A bus arbiter gives the controller absolute priority in RAM accesses while inserting read operations from the VME bus into unused clock cycles. In this way, dual-ported RAM is implemented efficiently.

In the design of this system, three aspects have been given major interest: robustness, flexibility, and performance.

Robustness: Since cable breakage is one of the main hazards found in sensory systems, reducing the number and length of cables is a major design issue. In the system presented, the analog circuitry is placed near the robot hand to keep the ribbon cables short. The longer line to the VME bus is a simple four-wire serial cable. This setup boils down diagnostics and repairs.

The buffering module automatically adapts to changing sizes of data packets, and guarantees constant data integrity. External reconfiguration of this module when changing the scan list of MASS is therefore unnecessary.

For additional safety, the controller cannot be interrupted or reprogrammed by the VME host. A watchdog mechanism guards against runaway code and ensures rapid error recovery. A timer measuring the delay between incoming packets is available to detect data inconsistencies.

Buffering data packets in a ringlike structure has proven to be very useful in recording time series, e.g. those shown in figures 6 and 8. For applications that are unable to perform calculations in real time, the buffer helps to interface the hard real-time process of data sampling to the soft real-time process of data analysis. This enables the applications to “catch up” on the incoming sensor data packets if they have been delayed, or to selectively observe the past of an event, e.g. measure the rate of change of the force signal when a slippage warning pulse has arrived, see fig. 8.

Flexibility: Several measures have been taken to make the experimentation system flexible. The analog signal preprocessing electronics are implemented as a plug-in module with very simple interfacing, which even allows using up to four different modules, permitting the simultaneous use of fingertips with different sensory equipment.

In order to match this hardware flexibility on the software level, the scan list of the A/D converter can be reprogrammed dynamically by software at any time. Since the buffering device adapts to any changes in the data packet size, this reconfiguration does not disturb the integrity of the buffer.

We intend to use the dynamic scan list reconfiguration to implement task dependent “adaptive sensing”, as it is often necessary to allocate a greater share of the total bandwidth to a specific sensor whose output is particularly interesting in a given situation.

Since the BRAD's buffer is available to all VME busmaster devices as shared memory, several processes can access the sensor data without danger of interference. Although this feature alone can provide much flexibility, we use a SORMA [7] service object instead to provide sensor data not only to programs running on the VME host workstation, but on any other workstation connected to the LAN. A dynamic sensor allocation scheme is planned, whereby client programs can request certain sensors to be scanned. The service will then reprogram the scan list if necessary, to suit the needs of all clients. This includes task-dependent sensing, as described above.

Performance: As an example application using the network to transmit sensor data, a monitoring program has been developed to visualize the output from the force/position sensors and the slippage detector from up to four identical fingers. In this setup, the data packets contain 36 sensor values. The rate at which the sensors are sampled and the history is updated is 520 Hz, and the plotting rate of the monitor program (implemented in Tcl/Tk) is 6 Hz.

Another example, in which the system has been used for time series recording, is the compound measurement shown in fig. 8. Here, eight sensor values (force sensor readout and analog signal from slippage detector, each contributing four values) and the edge detector output are transmitted in one scan. The scan rate is 2.3 kHz. The analysis program makes extensive use of BRAD's history buffer to ensure error-free recording.

The fastest scan rate that can be achieved using this system is 3.6 kHz delivering four sensor values per scan. The maximum age of data in the history buffer is the reciprocal sampling rate plus about 35 μs delay between sampling an analog signal and arrival of the data in the buffer. The A/D converter uses a charge redistribution method for digitizing with a precision of 8 Bits and $1/2$ Bit quantization error.

4 Summary

A tactile sensor system has been presented consisting of a fingertip prototype and hardware infrastructure to make sensor data easily available. The fingertips are specially designed for the robot hand in our laboratory to implement force feedback and reflex mechanisms. To this end, the fingertips have been equipped with two different types of sensors arranged in layers for simultaneous measurement of contact force and position information and slippage detection.

Two hardware components introduced in this paper, MASS and BRAD, provide a data acquisition and transportation system with a maximum delay of about 35 μs between sampling an analog signal and depositing the data in dual-ported RAM. The system is flexible enough to handle a large variety of sensors with little effort.

For easy experimentation with the tactile sensors, the system has been made available to multiple clients via the local area network. Since all other hardware components in the laboratory are accessed in a similar way, this simplifies the task of writing applications that use distributed hybrid hardware.

With this experimentation system at hand, we intend to further explore the areas of real-time grasp control and tactile exploration.

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