

Integrating force, tactile and proximity sensing for a flexible robotic system through a modular design

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ABSTRACT

For flexible manufacturing, namely parts assembly, the development of robot manipulators with the capacity of executing reliable fine motions with a high degree of generality is required. This requirement leads to the need of using sensors and consequently imposes the need of searching for techniques for efficient processing and integration of sensory data. This paper addresses issues regarding the integration of sensors for flexible robotics, namely force/torque, tactile and proximity range sensors. Here, we are essentially concerned with sensory integration for fine motion control, the following subjects being addressed: the architecture of the control system integrating force/torque, tactile and distance sensors and algorithms for sensor-based control.

1. Introduction

Flexible robotic systems, for example systems to be used in parts assembly automation, require robot manipulators featuring among other capabilities, the capacity of executing reliable fine motions with a high degree of generality. Fine motions should be understood as motions guided by task space sensory feedback, that is, movements controlled in closed loop by using task space sensory feedback and at the end giving to the robot the capacity to adapt itself according to the state of the environment. For this purpose, it is obvious that the robot should be equipped with sensors and consequently with the necessary means to perform the operations of acquisition and data processing. Only by using sensors it will be possible to deal with the uncertainties always present in real tasks, and accordingly to aim at the execution of different tasks with considerable autonomy and flexibility. Robotic systems using sensory information in a wide sense and in an efficient way are not yet available for industrial applications. A large spectrum of problems must be researched and solved before the development of such flexible sensor-based systems come to be a reality. Those problems arise at different domains from the

need of sensors and actuators with enhanced characteristics to algorithmic levels where the development of general solutions and methods, for example for 3D world representation, sensor fusion, geometrical reasoning and sensory planning strategies are indispensable. With the purpose to investigate problems in the domain of sensory robotics several research problems are being undertaken. The ultimate goal is to develop a robotic assembly cell, for which task we are currently using a PUMA 560 robot and a set of sensors including vision cameras, force/torque, tactile, distance and optical proximity sensors [1]. In this paper we address issues regarding the integration of sensors for controlling an industrial robot manipulator, namely the integration of force/torque, tactile and distance sensors. The integration issues and results presented here are, however, exclusive of the lowest-level control structure of the cell. In order to clarify our meaning of lowest-level control structure, we briefly address basic concepts regarding the overall control system under development. In functional terms, the overall control system can be categorized in three hierarchical levels: a planning and high-level information processing structure at the top of the hierarchy, a logic branching control structure at the intermediate level and a real-time *continuous* control structure at the bottom of the hierarchy.

In physical terms, the VAL-II controller of the PUMA robot is connected to the intermediate control level through the Supervisory Communication Channel (using the Digital Data Communications Message Protocol), and is connected to the lowest control level through the Real-time Path Control channel (RPC). The RPC channel allows the external control system to specify and modify the robot's trajectory in real time at a rate of 36 Hz, that is, the lowest-level layer allows the implementation of fine motions. At this level, a key point is the specification of the control laws (for position and force control) incorporating task space sensory feedback. In the next sections we address the following subjects: 1) architecture of the system integrating force/torque, tactile and distance sensors for fine motion control; 2) experimental validation of algorithms for sensor-based control.

2. Architecture of the processing system for fine motion control

In this section we describe the processing system used at the lowest control level whose architecture is shown in the schematic of the Fig.1. As Local Supervisor we use a PC 386SX equipped with the following boards: a microcontroller-based board responsible for the real-time path control communication; a Bitbus slave board to connect the system with hierarchically higher control levels; and TMS320C30 DSP based boards [2], dedicated to the data processing and to the implementation of the control algorithms. As shown in Fig.1, the system is structured hierarchically by four functional levels. At the bottom of the hierarchy we have the transducers and actuators. The next higher level is composed by the preprocessing systems carrying out the operations of conditioning, anti-aliasing filtering, analog-to-digital conversion, tactile array scanning and PWM signal generator to control the opening/closing movements of the fingers of the gripper. The analog-to-digital conversions, except for the ASTEK force

sensor, are performed in a similar way. We use 12-bit ADC converters with serial output allowing the implementation of the complete process of analog-to-digital-to-serial-to-parallel-to-FIFO storage, from the remote pre-processing boards to the microcontroller-based processing level, to be accomplished in a minimum time of the order of 7 μ sec. The pre-processing modules were designed to be placed on the manipulator arm close to the transducers. These are connected to the higher level through digital and power links. The signal digitalization at the preprocessing level is justified since this procedure provides better noise immunity than transmitting the analog versions. At the next higher level, operations such as signal linearization, frame formatting of the raw data and the configuration of the acquisition and actuation modes are fulfilled. This layer is microcontroller-based and is connected to the Local Supervisor through serial links (RS232 and synchronous serial link according to the DSP processor serial interface).

For the real-time path control communications we have developed a PC-AT bus board based on a microcontroller of the Intel MCS51 family. It has serial interfaces, RS232 and RS485, allowing its use as a node in a Bitbus network. The memory addressing space of the board is also mapped into the memory space of the PC-AT. Besides this facility for downloading programmes and data, the module has a multiprocessor interface device which provides a parallel, asynchronous communication channel for passing messages and data between the two processor systems. This circuit implements a shared memory space with logic to resolve access conflicts, that is, it implements a mutual exclusion logic.

The software which implements the real-time path control communication is divided into two physically separated modules. One module is written in PL/M-51 and lies in the previously described board. This programme was designed to maintain the real-time communications in a running state overcoming the tight demands of time imposed by the VAL-II system. It consists of the lowest-level protocol layer leaving the PC for the processing of application software.

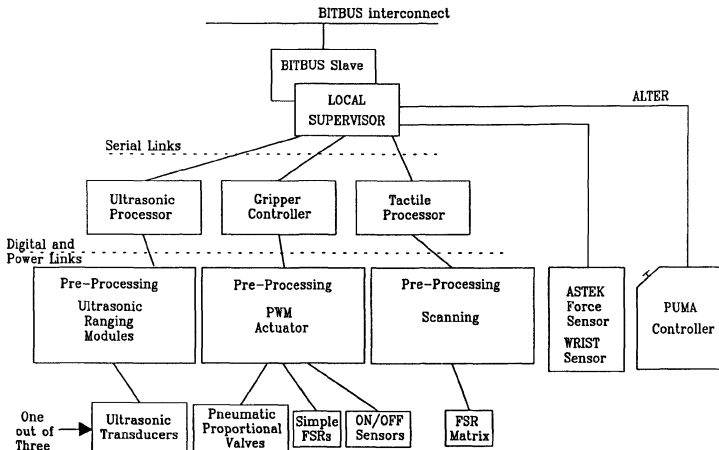


Fig.1 - Architecture of the sensory system for fine motion control

The second software module is a PC resident programme performing the interface between the lowest-level layer and the application software. From the user point of view this module appears as a set of procedures which allows him to control the robot's trajectory in real time. Once the normal communications state is achieved (the running state) the application programme has accessible data concerning the state of the communication and the set-point (or current-location) of the end-effector. Additionally, this interface is in charge of sending control data to define/modify the robot's trajectory. The exchange data rate is fixed at the value of 36 Hz. To provide for the task's synchronization the interface can trigger synchronous interrupts related to the start of each message from VAL-II.

Ultrasonic ranging system

For the measurement of distances we use ultrasonic sensors from Massa Products Corporation. Each sensor is basically composed by an ultrasonic ranging module and a single transmitter and receiver transducer. For a description of the ultrasonic system and methods to obtain three dimensional information using the system see [3,4].

Tactile sensing

The development of tactile sensors based on different technologies have been researched [5], namely the following types: Capacitive, Optoelectronic, Piezoelectric and Piezoresistive (sensors using metal and semiconductor strain gauges and sensors using conductive elastomers and carbon fibers). The underlying idea in all of these sensors is to produce, and estimate a function that describes the relationship between distributed pressure and some electrical property (current, inductance, voltage, or capacitance). All these technologies exhibit advantages and disadvantages. However, the piezoresistive approach has deserved larger attention in the scope of robotics. This fact is due to some characteristics that this technology offers in the construction of tactile matrices. This approach can lead to reasonable tactile solutions achieving good characteristics such as: high spatial resolution, miniature packaging, robustness, low cost enabling economical replacement and simple circuitry requirements. We are developing a 256 element tactile sensor using a piezoresistive thick-film polymer manufactured by Interlink which is referred as force sensing resistor (FSR) matrix. The transducer provides a spatial resolution of 0.156 cm with a sensing area of 2.5 cm x 2.5 cm. The pre-processing board has the scanning array circuit which implements a pixel isolation technique similar to those described in [6,7].

Force sensing

In parts assembly it is required that the robot comes into physical contact with materials, and continuous force control is necessary. Compliance can be achieved by using passive and/or active methods. Passive methods can be implemented by using mechanical elastic devices as the remote center compliance (RCC), or its enhanced

version - the instrumented remote center compliance (IRCC), which also provides displacement sensing [8]. Wrist force sensors for sensing contact forces are used in active compliance. The most popular wrist sensors, available commercially, are stiff sensors of strain-gauge type. It has been widely reported that using a stiff sensor in a stiff environment causes dynamic instability [9]. It is easy to ascertain that force control is essentially high-gain position control [10]. This high-gain results from the multiplication of the stiffness of the environment by the force control gain. There are a few number of ways in which this stability problem can be overcome. One solution for the problem might be to use a combined stiff-compliant sensor as described in [11]. However, the introduction of passive compliance in the wrist sensor leads to loss of position resolution and reduction in the dynamic bandwidth. Another similar solution is to dominate the stiffness of the environment by using a soft skin covering the fingers of the robot. Another approach to solve the stability problem using only a stiff sensor has been reported by C.H.An et al [10] relying on a fast open-loop joint torque control, to provide stability, and a lower bandwidth outer loop with wrist force sensing to provide extra accuracy. In the experimental validation of the control algorithm, a robot with direct drive actuators was used (the direct drive approach does not impose the need of gearing such as anti-backlash gears which are greatly responsible for a large component of friction as in conventional Direct-Current (DC) actuated robots).

We are using a stiff ASTEK FS6-100A six-axis force sensor of strain-gauge type. The sensor carries out the signal conditioning process and formats the force information in the form of a RS-232 serial data stream. The sensor resolves data into a specified orthogonal coordinate frame at a measurement rate up to 240 Hz. Currently we are working on the development of algorithms for force control by analyzing the behavior of the robot manipulator when constrained by different stiffness materials. Two curves representing the force function of distance, for the robot in contact with a 3mm silicone rubber and a low-stiff spring, are illustrated in Fig.2. The goal is to use the force control in environments that exhibit a natural compliance or in stiff environments but by using fingers covered by a soft skin, for example of silicone rubber.

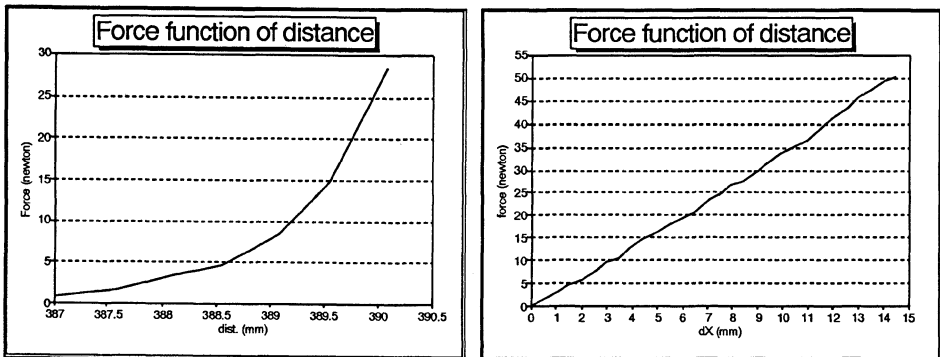


Fig.2 Force function of displacement:
 a) 3 mm thickness silicone rubber (left) b) soft spring (right)

3. Ongoing work on control using task-space feedback

The sensory loop for each sensor at the fine motion control level is supported by a computational structure of the form illustrated in the Fig.3. For task's synchronization, the Alter interface board generates an interrupt signal in synchronism with the start of each message from VAL-II. By receiving this signal, both the PC-AT and the microcontroller based modules initiate a new cycle of data acquisition and data processing. The microcontroller board performs the signal acquisition and data formatting according to the pre-programmable mode and configuration. Per each set of data samples, the board sends it to the DSP board with information of the number of the set. The DSP board initiates its processing stage as long as the first packet of samples is received and finishes it some time after the reception of the last packet. The final operation consists on the transfer of the results from the DSP board to the Alter interface board. These results must be present at the Alter board some time before the beginning of the next cycle of 28 ms, a time greater than a critical time of the order of 1 ms (see Fig.4). If this time requirement is met, then the board guarantees that the transformation data will be transmitted to the VAL-II in the next time interval. The timing diagram of the running stages of sensor data manipulation is shown in Fig.4. From the above considerations, we can say that in the normal situation each complete sensor data processing is accomplished in a single time interval, that is, it is responsible for a single delay term in the sensory control loop. It should be noted, however, that there is an additional delay due to the time spent in the data transmission to the VAL-II system, which can not be avoided given the low transmission rates allowed by the VAL-II.

In the design of algorithms for sensor-based control, the kinematic and dynamic constraints must be taken into account. With regards to the dynamic constraints, an accurate model of the real time behavior of all the task's components, including the manipulator, its controller, sensors and materials to be handled, must be estimated. In the identification of the manipulator dynamics, including the time delays caused by the overall control system, we have followed an approach of considering it as a black-box

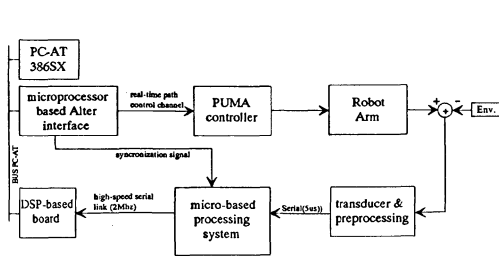


Fig.3-Feedback processing system for each sensor

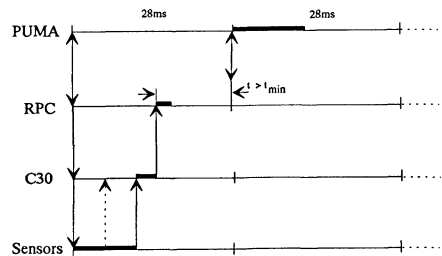


Fig.4 - Timing diagram of the sensory system

problem. Thus it was only considered the input/output relationship without using any a priori knowledge of the dynamics of the manipulator structure or of the behavior of its controller system. A set of experiments has been conducted in order to estimate an accurate model of the system dynamics. However, this effort was limited in describing the dynamic behavior within a narrow bandwidth (limited to the bandwidth of the real time path control interface and for low velocities). The Puma response to an Alter position command of a combination of sinusoids of the form

$$x(i) = 5\sin\left(\frac{2\pi i}{71}\right), \{i=0..70\}; 2\sin\left(\frac{2\pi(i-71)}{90}\right), \{i=71..160\}; 4\sin\left(\frac{2\pi(i-161)}{40}\right), \{i=161..200\},$$

is depicted in the Fig.5. This command was issued in cumulative mode and directed to change the cartesian position of the robot according to the z-axis of the world coordinate system. The actual position was obtained by using the ultrasonic system. This is an example of a set of experiments conducted to the identification process. In all the experiments, a special care was taken into account to guarantee that the input command behaved has a persistently exciting input [12]. Using the Matlab identification Toolbox, the results described in the Table I, were obtained .

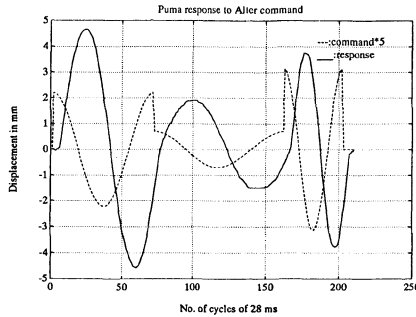


Fig.5 Puma response to an Alter position command of a combination of sinusoids

Table I

Polynomial coefficients and standard deviations obtained from the identification process				
Model/ Method	Nº of zeros, poles, delays	A	B	C
ARX	[1 1 5]	1 -1.0017 0 0.0013	0 0 0 0 0 0.9155 0 0 0 0 0 0.0133	
ARX	[2 2 4]	1 -0.912 -0.092 0 0.050 0.050	0 0 0 0 0.0929 0.904 0 0 0 0 0.054 0.070	
IV4	[2 2 4]	1 -1.1 0.1 0 0.059 0.059	0 0 0 0 0.086 0.737 0 0 0 0 0.048 0.079	
ARMAX	[2 2 2 4]	1 -1.072 0.0705 0 0.0604 0.0608	0 0 0 0 0.083 0.764 0 0 0 0 0.050 0.0815	1 -0.296 0.229 0 0.098 0.0789

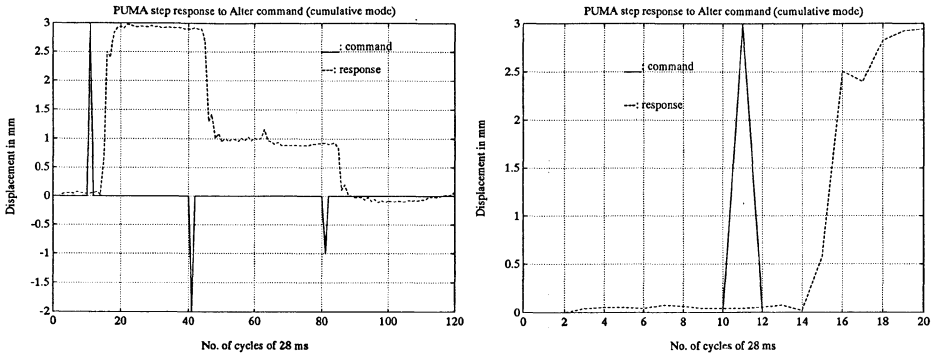


Fig.6 - Puma Step response: a) complete view (left), b) partial view (right)

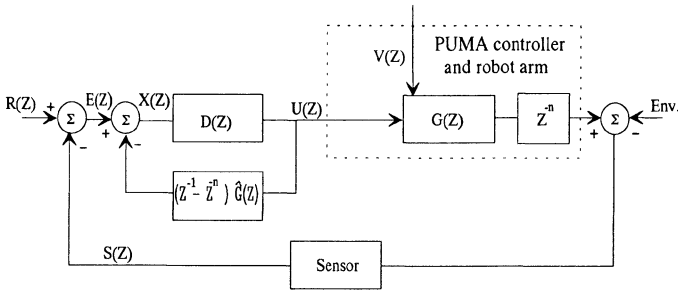


Fig.7 Feedback position control

From these results it can be concluded that the dynamic response of the system is dominated by a five delay term (it must be highlighted that this result includes the two delays due to the external system). This conclusion is reinforced in the graphics of the Fig.6 which describes the Puma step response to an Alter position command. The fact that the system dynamics is dominated by pure delay times, led us to base the position control law on the Smith predictor concept [13].

The basic position control law is depicted in the block diagram of Fig.7, where $G(Z) \cdot Z^{-n}$ represents the estimative of the transfer function of the complete system.

Results of the application of a command to position the end-effector at a distance of 245 mm above the surface, issued at the time 1 and by using the position control algorithm, are show graphically in Fig.8. A proportional feedback was used in both experiments. The left graphic shows the Puma response for different proportional gains using $(0.92/(1-Z^{-1})) \cdot Z^{-5}$ as estimative of the transfer function. The right graphic shows the Puma response using different transfer function estimatives and control algorithms. Two of the curves are related to the use of the Smith predictor with different transfer function estimatives, while the third curve was obtained by using only proportional feedback (for $K_p > 0.1$ exhibits overshoot as in the case of Fig.8).

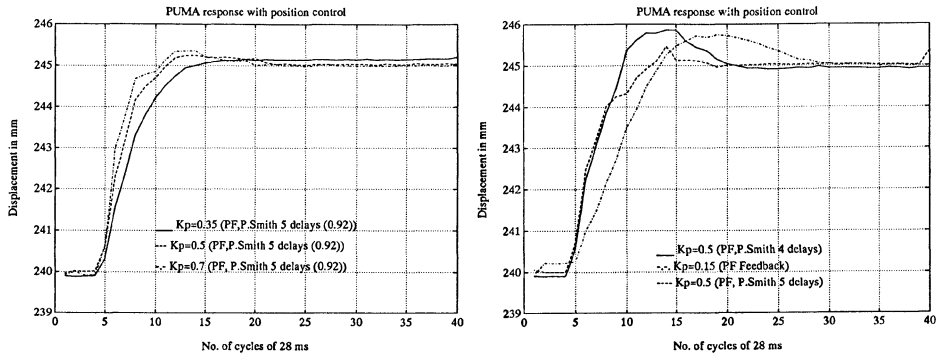


Fig.8 - Puma responses with position control

4. Conclusions

In this paper issues regarding the integration of sensors for controlling an industrial robot manipulator were addressed, particularly integration aspects related to the control level. A similar effort, as applied for position control, has been conducted for force control. The next step will be to research in fine motion planning by using several sensors.

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