Traditional and Non-Traditional Robotic Sensors

Traditional and Non-Traditional Robotic Sensors

Edited by

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Preface

This book contains the written record of the NATO Advanced Research Workshop on Traditional and Non-Traditional Robotic Sensors held in the Hotel Villa del Mare, Maratea, Italy, August 28 – September 1, 1989. This workshop was organized under the auspicies of the NATO Special Program on Sensory Systems for Robotic Control. Professor Frans Groen from the University of Amsterdam and Dr. Gert Hirzinger from the German Aerospace Research Establishment (DLR) served as members of the organizing committee for this workshop.

Research in the area of robotic sensors is necessary in order to support a wide range of applications, including: industrial automation, space robotics, image analysis, microelectronics, and intelligent sensors. This workshop focused on the role of traditional and non-traditional sensors in robotics. In particular, the following three topics were explored:

- Sensor development and technology,
- Multisensor integration techniques,
- Application area requirements which motivate sensor development directions.

This workshop brought together experts from NATO countries to discuss recent developments in these three areas.

Many new directions (or new directions on old problems) were proposed. Existing sensors should be pushed into new application domains such as medical robotics and space robotics. Much work is required on the development of silicon sensors and model-based sensors. The integration of olfactory sensors seems a useful step. Error recovery for sensors, as well as maintenance and prognosis of sensors, needs to be addressed. It would be very useful to have adequate sensor simulations for a wide range of sensors. It appears that internal sensors will switch from strain gauges to induction-based sensors; this needs to be developed. Inertial sensors need to be incorporated in the sensor-based control loop for robotic systems. In the context of active sensing, it is necessary to define the relation between quantitative versus qualitative sensing and sequencing and integration of sensing with the given task. Behavioral specifiactions seem to offer an approach to this problem.

One major problem that arose was the definition of tactile sensors; just what does a tactile sensor measure? It seems necessary to distinguish at a high level between the cutaneous and kinesthetic properties of tactile sensors. Another concern is the field performance of commercially available sensors, as well as the requirement of a meaningful set of specifications for a sensor. It seems that it may be necessary to retrofit sensors to existing robots, and this may pose some problems. Another major concern is the fact that the development of sensor systems is tied to commercial develbpment, which puts a premium on industrial needs rather than general research needs. It might also be useful if there existed an integrated testing lab for sensors and associated software systems. Of immediate concern is the lack of fast sensor and controller interfaces. Furthermore, many participants felt the need for torque sensors at robot joints. Finally, safety issues with sensors have yet to be dealt with adequately.

The papers in this volume constitute a cross-section of the current research in robotic sensors and motivate the new directions and problems summarized above. We were quite fortunate to obtain such an excellent group of active researchers to participate and contribute to this workshop. In addition, another major goal of this NATO program was met, in that the group mixed very well socially, and we all made new acquaintances from the NATO research community. This kind of meeting provides a wonderful opportunity for the detailed exchange of ideas which, in turn, motivates further research cooperation among the participants.

Finally, I would like to thank all the people who helped make the meeting possible and who saw to it that it ran smoothly: the staff and management of the Hotel Villa del Mare, and Vicky Hawken from the University of Utah who handled the administrative details of the meeting with wit and charm.

Salt Lake City
March 1990

Thomas C. Henderson

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Fast Sensory Control of Robot Manipulators

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Abstract: A positional deviation sensor for contact-free physical guidance of a manipulator is described. The manipulator is set to track a motion marker close up. Factors limiting and means for improving the performance are pointed out. The result is a system that can be used for real-time training of spray-painting robots. The means are easily extened to general sensory control.

1. INTRODUCTION

This contribution presents a new system for contact-free positional sensing of a tool or teach-handle moved freely by the operator (Balchen, 1984; Dessen, 1987; 1988). It consists of a small-range positional deviation sensor (PDS) mounted at the tip of the manipulator. A motivation for employing the positional deviation sensor is given by considering the programming of a paint spraying robot. During the training session, the operator holds the spray-gun in his own hands, and carries out the task in his usual manner. At the same time, the robot manipulator follows the tool slavishly, without any contact. The situation is shown in Fig. 1. The manipulator is able to track the tool because of feedback from the PDS, in a similar manner to using a force sensing handle for the same purpose.

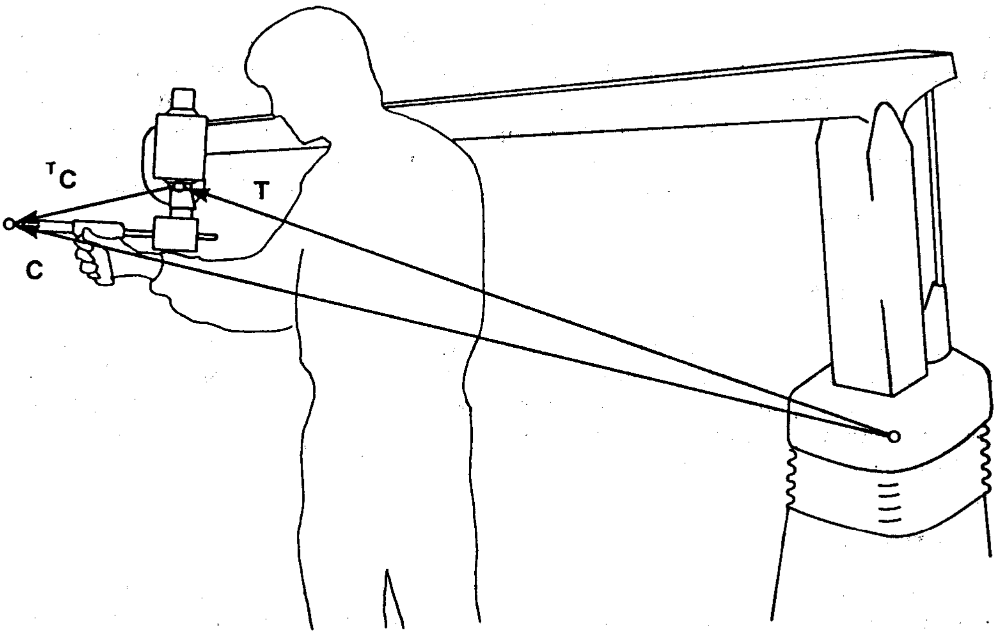

Figure 1. Manual lead-through programming

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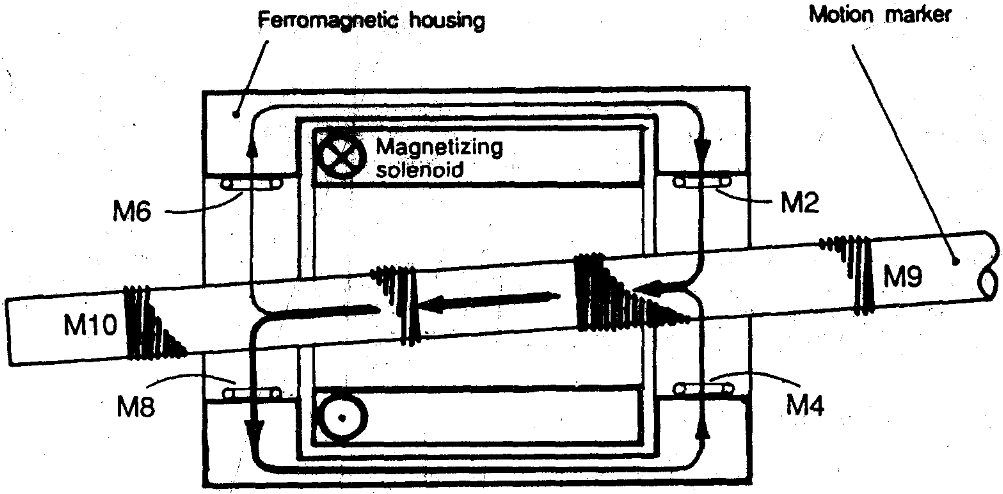

Figure 2. Measurement sensor. Flux through each solenoid varies according to motion.

The PDS consists of two complementary parts; one fixed to the tool, and the other to the wrist of the manipulator. These two parts are made of ferromagnetic material, Fig. 2, and are magnetized in opposite axial directions by means of a solenoid mounted inside the larger, hollow part. This creates a radial magnetic field between them which varies according to their relative position. By measuring the magnetic field at selected points, relative motion is monitored.

Details on the system are presented in (Dessen, 1988). Presented below is a discussion of problems concerning high-speed tracking of the tool marker. First, tracking performance is discussed in terms of a simple 1# (degree of freedom) system, reviwing basic servo system concepts. Means for improving the performance are sought in two directions, the first one being to increase the system bandwidth by means of internal feedback. The second involves optimizing the use of the sensor's range by introducing a special coordinating controller

2. TRACKING SYSTEM

The success of the complete training system relies on the presence of a control system which makes the manipulator follow the tool closely at all times. Especially, real-time training of paint spraying robots requires outstanding velocity and accelerational capabilities. The purpose of this section is to outline a coordinating control structure and to point out factors that limit its performance.

2.1. Servo coordination

Very often, playback control systems work in servo coordinates. This means that any motion reference is converted into a vector of servo references. A corresponding vector $\mathbf{e}$ of control errors is used to compute the required action. With the PDS, no servo reference is available. It is easy however to produce the control error in servo coordinates directly from the deviation sensor data, vector ${}^{M}\mathbf{d}$. The relationship is usually represented by the first-order approximation

$$^{\mathbf{M}}\mathbf{d} = \mathbf{J}_{\mathbf{eM}}\mathbf{e} \tag{2.1}$$

where $\mathbf{J}_{\mathbf{eM}}$ is the Jacobian matrix $\partial\,^{\mathbf{M}}\mathbf{d} / \partial\mathbf{e}$. If it is nonsingular, the control error may be computed by

$$\mathbf{e} = \mathbf{J}_{\mathbf{Me}}\,^{\mathbf{M}}\mathbf{d} \qquad \text{where} \qquad \mathbf{J}_{\mathbf{Me}} = \mathbf{J}_{\mathbf{eM}}^{-1} \tag{2.2}$$

Often, $\mathbf{J}_{\mathbf{Me}}$ will not be computed explicitely. Instead $^{\mathbf{M}}\mathbf{d}$ will go through a sequence of intermediate differential tranformations until finally $\mathbf{e}$ is obtained.

Once $\mathbf{e}$ is given, controllers working in joint coordinates can be applied. The usual approach at this level is to employ separate controllers for each servo, neglecting possible coupling between the actuators. In many cases, this assumption is reasonable though not completely true. In the present case, coupling will be neglected by assuming it to be taken care of by internal control. More precisely, internal speed control of N servos is assumed with a resulting transfer matrix

$$\mathbf{G}(s) = \mathrm{diag}[g_1(s), g_2(s), \ldots, g_{\mathrm{N}}(s)] \tag{2.3}$$

which relates actual speed and speed reference by

$$\dot{q}_i(s) = g_i(s)\,\dot{q}_{i0}(s)$$

Seen from an added positional controller, the process transfer matrix is

$$\mathbf{H}(s) = \frac{1}{s}\,\mathbf{G}(s) = \mathrm{diag}[\tfrac{1}{s}\,g_1(s), \ldots, \tfrac{1}{s}\,g_{\mathrm{N}}(s)] \tag{2.4}$$

In practice $\mathbf{H}(s)$ will include several off-diagonal coupling terms. However, these are assumed to be taken care of by the speed controller.

The outlined structure may be considered as a hierarchical control system where the higher level is a coordinating positional controller whereas the lower level performs decoupling speed control. This partitioning will be used throughout since it is believed to give a better understanding of the control problem at hand.

2.2. Performance

It is of interest to have a rough idea of the expected tracking performance. For this purpose, a simple 1# positional control system will be considered. Conforming to (2.4), the process transfer function is written

$$h(s) = \frac{1}{s}\,g(s) \tag{2.5}$$

The control system will be analyzed in terms of its open-loop transfer function, which is assumed to be stable. At first, a proportional controller with gain k_{p} will be applied. It follows from the Bode-Nyquist stability criterion that the closed-loop system will be stable whenever

$$k_{\mathrm{p}} < \alpha\omega_{\varphi} = \omega_{\mathrm{x}} \tag{2.6}$$

where ω_φ is the $-180\,°$ phase shift frequency for $h(j\omega)$, and $\alpha = |\,g(j\omega_\varphi)|^{-1}$

In order to obtain simple expressions for the performance, controllers are assumed to be designed using the Ziegler-Nichols method, where control parameters are based on the values of ω_x and ω_φ. For a proportional (P) controller, the method yields

$$h_r(s) = k_p = 0.5\,\omega_x \tag{2.7}$$

The resulting open-loop transfer function becomes

$$h_0(s) = h_r(s)h(s) \tag{2.8}$$

Tracking performance will be studied in terms of the closed-loop error transfer function

$$N(s) = e(s)/q_0(s) = \frac{1}{1 + h_0(s)} \tag{2.9}$$

since the relationship between reference and control error is

$$e(s) = q_0(s) - q(s) = q_0(s) - h_0(s)e(s) \tag{2.10}$$

Assuming that the control error amplitude is restricted by $|e(j\omega)| < E$ for all real ω, the reference is restricted by

$$|\,q_0(j\omega)| < E\,|\,N(j\omega)|^{-1} \tag{2.11}$$

Hence, the allowed tool motion amplitude is closely related to the allowed positional deviation, and may for any single frequency ω be obtained almost directly from $N(j\omega)$.

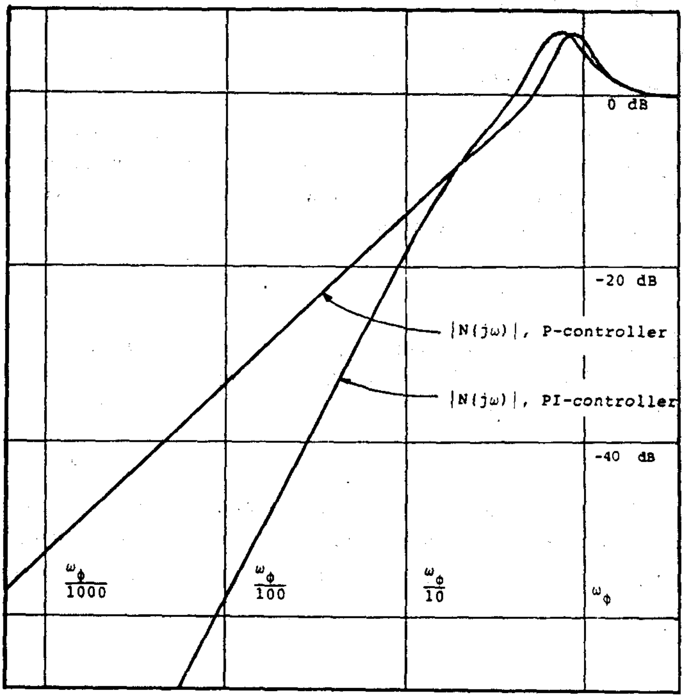

Figure 3. Amplitudes of typical closed-loop error transfer functions for P and PI type servos. Low amplitude means good performance.

By studying the asymptotical behaviour of $N(s)$ as s approaches zero, it is seen that a maximum steady-state velocity of

$$v_P = \lim_{s \to 0} \frac{sE}{N(s)} = E\,k_p = 0.5\,E\,\omega_x = 0.5\,E\,\alpha\,\omega_\varphi \qquad (2.12)$$

is obtained. Since the range of the PDS of order ±1cm only, the resulting speed will often be low. A proportional plus integral (PI) controller, where

$$h_r(s) = k_p\,\frac{1 + T_i\,s}{T_i\,s} \qquad (2.13)$$

will by the Ziegler-Nichols method be assigned

$$k_p = 0.45\,\omega_x \;;\; T_i = 5/\omega_\varphi = 5\,\alpha/\omega_x \qquad (2.14)$$

This time, the asymptotical behaviour of $N(s)$ implies unbound velocity with a maximum steady state acceleration

$$a_{PI} = \lim_{s \to 0} \frac{s^2 E}{N(s)} = E\,\frac{k_p}{T_i} = \frac{0.45}{5\,\alpha}\,E\,\omega_x^2 = 0.09\,E\,\alpha\,\omega_\varphi^2 \qquad (2.15)$$

Compared to the use of a proportional controller, this is an improvement. However, the servo may still react slowly.

Performance measures v_P and a_{PI} are used often in place of function $N(s)$ since they give an immediate understanding of important properties of the system in question. Whenever v_P is used, it is understood that the underlying closed-loop error transfer function has the slope +20 dB/decade at low frequencies. Whenever a_{PI} is used, this slope is understood to be +40 dB/decade. For both P and PI control, sample Bode plots of resulting error transfer functions are shown in Fig. 3.

As seen from (2.12) and (2.15), the performance depends on the deviation sensor by E and on $g(s)$ by α and ω_φ. Trivially, E may be increased by enlarging the positional deviation sensor. A second approach is to coordinate the servos so that maximum use is made of the existing sensor range. This is considered in § 6. Due to the second order dependence on ω_φ in (2.15), means for improving the lower-level control system are of special interest. Such means are discussed in §§ 7 and 8.

2.3. Force sensing handles

During the initial experiments, it was of interest to compare the PDS with a force sensing device. For a moment, the space between the two parts of the sensor was packed with rubber foam in order to obtain mechanical contact with a reasonable stiffness. The result was a more stable system, however the sensor workspace was reduced because of the foam, and now considerable force had to be applied in order to make the manipulator move.

Consider now the possibility of making use of the improved stability to increase the controller gains. This again will increase the performance of the system. A quick stability analysis can be made by assuming a certain stiffness k_s between the two parts of the sensor,and that the human operator represents a stiffness k_h. Defining the position of the operator and the manipulator as q_0 and q respectively, the position of the tool marker will be found as

$$q_m = \frac{k_s q + k_h q_0}{k_s + k_h} \tag{2.16}$$

The control error is defined as $e = q_0 - q$ whereas the measured control error is

$$e_m = q_m - q = \frac{k_h}{k_h + k_s} e \tag{2.17}$$

This effect results in a corresponding damping of the original feedback gain, which now can be increased to

$$k_p = 0.5\ \omega_x \frac{k_h + k_s}{k_h} \tag{2.18}$$

according to (2.7) or a similar value corresponding to (2.14).

The problem is that the stiffness of the human muscular system varies according to the type of motion required, and will often increase during swift and precise motion. In that case the damping given by (2.17) will decrease, and if k_p is designed for a lower k_h than the actual value, the system may become instable. Safe design requires a large k_h to be inserted into (2.18), and as k_h increases, k_p approaches the value given by (2.7), which is the only one that is perfectly safe.

A more detailed analysis of the situation is presented in (Hirzinger, 1982). However, the above considerations provide a simple link between the stability problems encountered with a positional deviation sensor and with a force sensing handle. Moreover, simple stability criteria have been obtained for both cases.

3. INCREASING THE BANDWIDTH

Above, simple expressions were developed which relate tracking performance and process bandwidth. Assumed controllers were of the P and the PI type, subject to a process with internal speed control. What remains is to investigate how different internal controllers affect the performance. Dynamic models for the hydraulic servos of the TR-400 are developed in (Dessen, 1988). Neglecting possible coupling between the different axes,

$$g(s) = \frac{1}{1 + 2\zeta(s/\omega_0) + (s/\omega_0)^2} \tag{3.1}$$

is a good representation of a single servo, as seen from the higher level.