Robotica (1999) volume 17, pp. 17–21. Printed in the United Kingdom © 1999 Cambridge University Press

Fast sensor guidance of industrial robots – experimental results

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SUMMARY
For securing and increasing the quality of various material processing technologies a flexible sensor data integration is indispensable. Hence, a powerful and configurable sensor-robot-system was designed and implemented, integrating sensor data into industrial robot controls within the interpolation or the position control clock rate. Different controllers were designed and the system responses of the control loops were simulated and optimized by an efficient control design tool. Experimental results on the achievable path accuracy are presented.[1] Finally, some application for the developed sensor control loops are introduced.

KEYWORDS: Sensor guidance; Industrial robots; Processing technologies; Control loops.

1. INTRODUCTION

The commonly used industrial robot controllers possess only insufficient capabilities to integrate external sensor data. In various material processing technologies a flexible sensor data integration, especially a fast sensor guidance of robots, is indispensable to compensate differences between the desired robot path and the actual driven path. Typical applications are laser welding and assembly technologies. The geometrical relations between the tool and the workpiece are decisive for a secure guidance of the process. Without sensor integration the robot control cannot compensate workpiece contour variations, pose errors and robot path inaccuracy during processing. As a result, the product quality suffers.

In an industrial environment, manual teach-in programming is still a commonly used method.[2] In terms of time and work, this procedure is very exhausting and can be replaced by more efficient explicit or implicit off-line programming procedures. The essential draw-backs of the latter is due however, to the necessity of a very exact modeling of the robot and its environment.

Most of the mentioned problems can be solved by the integration of sensors. For example, the robot path of a laser beam processing can be adapted on-line to the desired path, by the use of sensor technology.

2. DESIGN OF A SYSTEM FOR SENSOR DATA PROCESSING

Due to the limited possibilities of commercial robot controls a fast and configurable interface for sensor data integration has been integrated prototypically in a robot control.

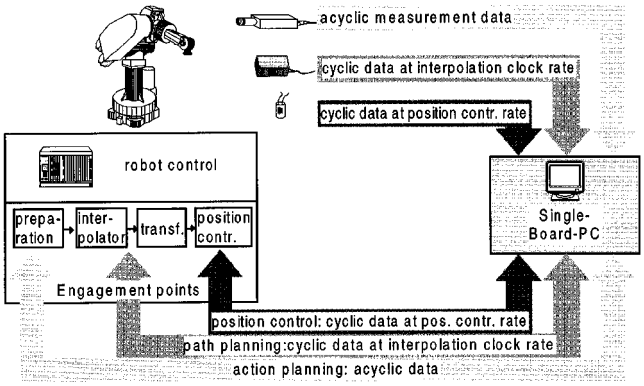


Fig. 1. Structure of the Sensor-Robot-System.

Fundamentally, there are three different possible engagement points for sensor data integration, within a robot control.

The used robot control provides two cyclic engagement points for bi-directional data transfer, within the interpolation and the position control clock rate (Figure 1). Additionally, the acyclic engagement point makes an acyclic data transfer possible. The cyclic integration of correction values allows an adaptation of the actual driven path. The sensor computer (Single-Board-PC) transfers data to the robot control within the levels action planning, path planning and position control.[3] Otherwise, cyclic data of the robot control is transferred to the sensor computer.

The acyclic engagement point enables the transfer of data within the robot program for influencing the flow of the robot program. In addition, this engagement point is used to build up a program control and an action control of the sensor-root-system, which can directly be served from the robot control (Figure 2). The program control offers the possibility of system tasks for activation/deactivation and

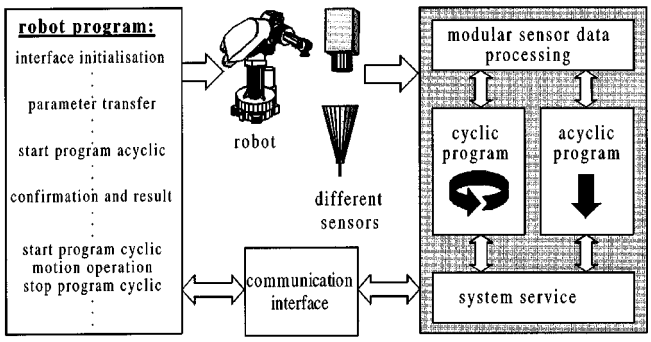


Fig. 2. Structure of the Sensor-Robot-System programming.

https://doi.org/10.1017/S0263574799001010 Published online by Cambridge University Press

start/stop of cyclic and acyclic user programs. Further, system tasks are responsible for the transfer of system or program parameters. Finally, system tasks are used to terminate the communication to the robot control or initialize the Single-Board-PC.

The robot controller communicates with the Single-Board-PC by using a common communication buffer (dual ported RAM), which can be read and written from both sides. The advantages of this solution are a high data transmission security combined with a high data transmission rate. In first investigations the Single-Board-PC, at that time equipped with an 80386-processor, had to be extended with a sub system, consisting of a transputer network with five processors.[4] This was necessary for calculating the correction values and coordinate transformations within the position control clock rate. Using a Single-Board-PC with an 80486DX2/66-processor now, the transputer network is obsolete. The Single-Board-PC also carries out the tasks of sensor data acquisition with own components which can scan analogous sensor signals with high clock rates.

3. SENSOR CONTROL LOOPS AT INTERPOLATION AND POSITION CONTROL CLOCK RATE

When building up a sensor control loop for path adaptation, a model of the controlled system has to be identified first. Here the controlled system is a position controlled robot.

3.1 Identification of the controlled systems

The controlled system is characterized by one cascaded control loop per axis, consisting of a current, a velocity and a position control loop. The velocity and current control loop are summarized by a resulting first-order time-delay element. An equal dynamic system performance of all axis can be reached by inserting a symmetry element into the position controller. With the correct choice of the time constant the system response is approximately not influenced by the robot kinematics. The symmetry element can be modeled by a first-order time-delay element. The position controller possesses no dynamic charateristics and is thus modeled by a constant.

Within the model of the controlled system at the interpolation clock rate the axis interpolator has to be taken into account. Several investigations came to the result, that it can be modeled by a second-order time-delay element. In addition, the controlled system contains a time-delay element with a time-delay of two interpolation clock rates and the arm of the velocity feed forward control.

For the identification of the two different controlled systems a Cartesian step in direction of the z-axis of the robot base coordinate system was used. A cyclic user program produced the step excitation. The step response of the controlled system was recorded by a high-precise distance measuring triangulation sensor. It possesses an accuracy of 30 μm. With the use of a least square error parameter identification method the controlled systems depict in Figure 3 were parametrized.

As one can see in Figure 4, the simulated step response is

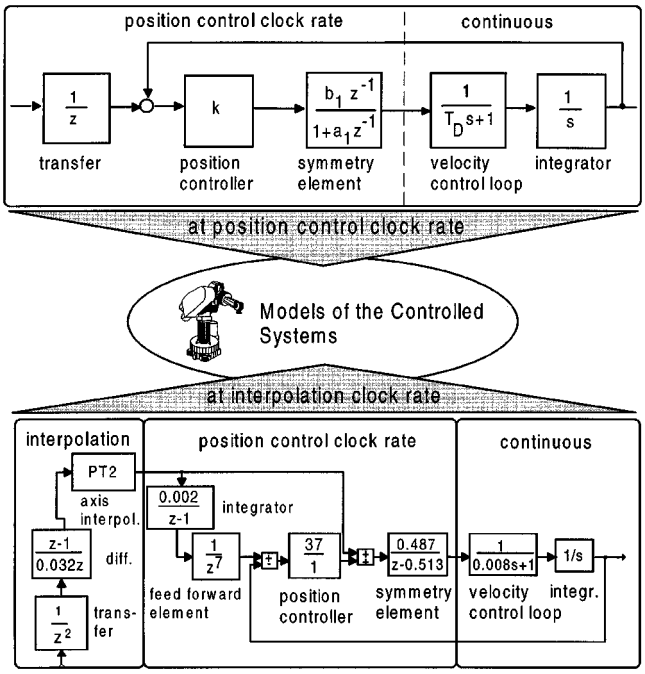


Fig. 3. Models of the Controlled Systems.

almost identical with the real one. Differences of the model can be explained by the use of a reduced model order.

First the time-delay of three interpolation clock rates (96 ms) is recognized at the step response of the controlled system at the interpolation clock rate. Later on, the system response rises very fast to the final value (190 ms). The system identification was carried out at different operating points and with various step amplitudes. As a result, only a small dependence of the step responses, concerning different operating points, can be recognized. As a result, it can be said that the controlled system at the interpolation clock rate possesses a behavior afflicted by a high time-delay. Thus, the desired value was not reached until 190 ms.

Consequently, the behavior of the controlled system, characterized by time-delays, has to be taken into account during the design of the sensor controller.

In contrast the controlled system at the position control clock rate has a very small rise and settling time of 65 ms (Figure 5) This can be attributed to time-delays which are basically smaller at this engagement point. The reason why the time-delays getting smaller are the reduced data transfer delays of two position control clock rates.

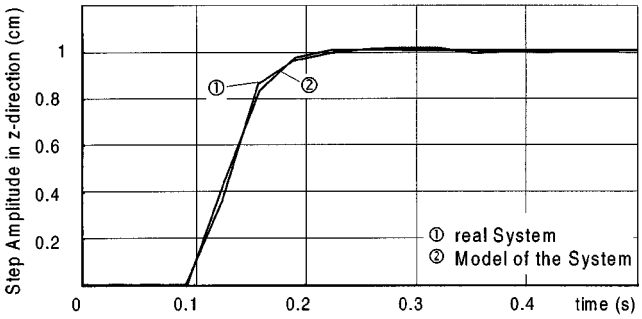


Fig. 4. Step response of the Controlled System within the Interpolation Clock Rate.

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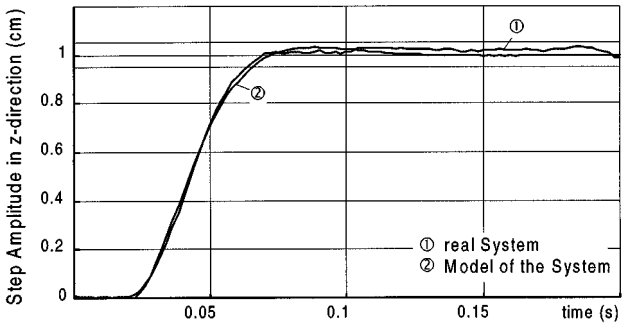


Fig. 5. Step response of the Controlled System within the Position Control Clock Rate.

3.2 Simulation and validation of the sensor control loop at the interpolation clock rate

To control processes, which are afflicted by time-delays, PI-, PID-, predictive and dead beat controllers have been examined. These controllers are next investigated, concerning both the simulative and the practical behavior.

The results of various controller investigations are summarized in Table I and can be compared directly. As an assessment scale, the essential characteristics of the step responses are shown. For comparison the characteristics of the controlled system are outlined too.

Because of the high time-delays the sensor control loop with PI- and PID-controllers possesses a bigger rise and settling time than the controlled system itself. On the other hand, the dynamic behavior of the sensor control loop can be improved with the use of predictive or dead beat controllers. The sensor control loop with the smith predictive controller shows the smallest rise time, but a high overshoot amplitude of 13% of the desired value. Consequently, the dead beat controller represents the best of the investigated solutions (Figure 6).

The sensitivity of PI- and PID-controllers toward operating point variations or faulty modeled time-delays is low. Predictive and dead beat controllers are more sensitive toward these kinds of model variations, because they principally use the compensation of poles and zeros of the controlled system. The dead beat controller is sensitive toward faulty modeled time-delays, but overall it has the best characteristics. The time-delay of the controlled system results of the time-delays during data transfer. These time-delays are well-known, so the disadvantages of dead beat controller have no effect. Consequently, the sensor control loop with dead beat controller is used for comparison with sensor control loops at the position control clock rate in the following.

3.3 Simulation and validation of the sensor control loop at the position control clock rate

For the sensor control loop at the position control clock rate first a PI-controller was investigated for the reachable dynamics. In Figure 7 a very good agreement on the step responses of the simulated and the real sensor control loop can be observed. After the rise time of 70 ms the controlled variable stays within a ±5% tolerance band around the desired value. The rise time of the sensor control loop is insignificantly higher than the rise time of the controlled system. Thus, the given demands can be fulfilled with a PI-controller. The controlled variable possesses only insignificantly higher values than the reference variable. As a result, the restrictions within the robot control are not exceeded, if reference variable steps are chosen within some limits.

Investigations carried out at different operating points confirm the presented results. The operating points are typical positions of the robot within its work space at characteristic material processing tasks.

4. COMPARISON OF THE RESULTS

In the following the results of the sensor control loops at the interpolation and the position control clock rate are compared and characteristics for the use of sensor control loops are given (Figure 8) The sensor control loop at the interpolation clock rate differs from the sensor control loop at the position control clock rate in its behavior afflicted with high time-delays. Thus, the controlled system at the interpolation clock rate possesses a rise time 2.9 times bigger than at the position control clock rate. The time-delay of the controlled system is a matter of principle and only a reduction of the interpolation clock rate can reduce

Table I. Comparison of different Controllers at the Interpolation Clock Rate.

	Controlled System	Control with PI-Controller	Control with PID-Controller	Control with Predictive Controller	Control with Dead Beat Controller
Rise Time (ms)	190	267	215	165	172
Settling TIme (ms)	190	346	215	220	172
Time-Delay (ms)	96	96	96	96	96
Rise Time without Time-Delay (ms)	94	171	119	69	76
Settling Time without Time-Delay (ms)	94	250	119	124	76
Overshoot Amplitude	3%	7%	4%	13%	2%
Sensitivity against Errors in the Time-Delay Modelling of the Controlled System	/	–	–	+	+
Sensitivity against operating point variations	/	–	–	+	0

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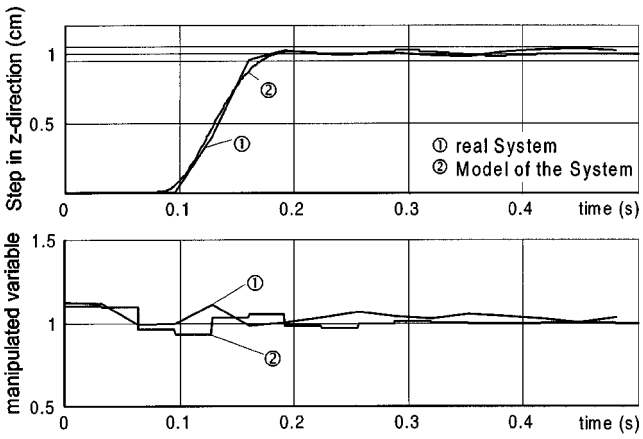


Fig. 6. Step Response of Sensor Control Loop with Dead Beat Controller (interpolat. clock rate).

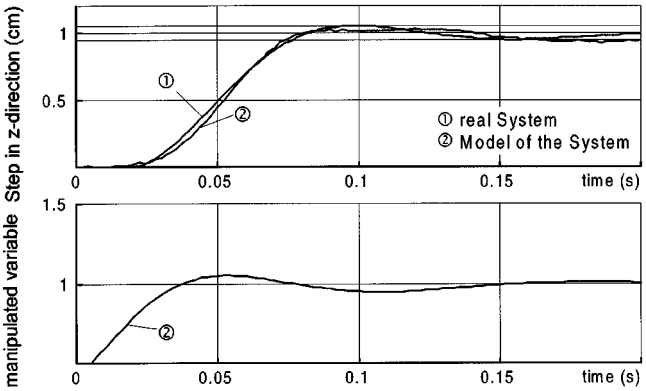


Fig. 7. Step Response of Sensor Control Loop with PI Controller (Position Control Clock Rate).

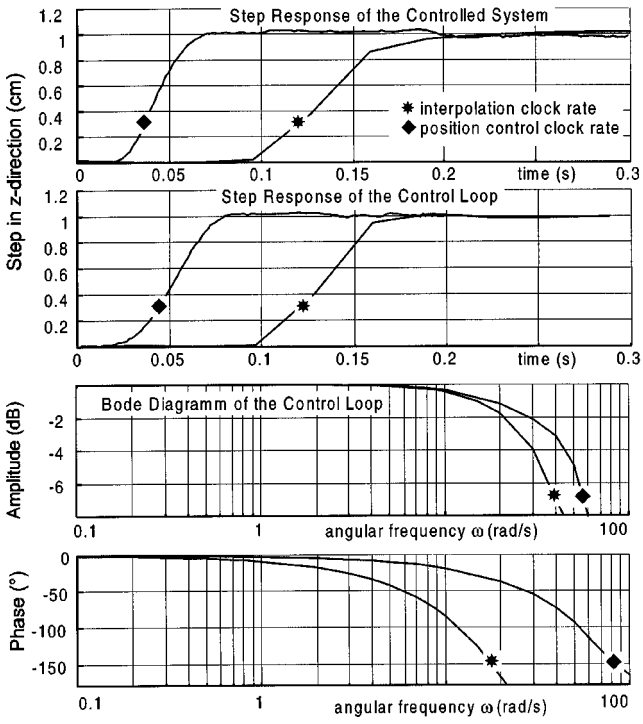


Fig. 8. Comparison of Sensor Control Loops at Interpolation and Position Control Clock Rate.

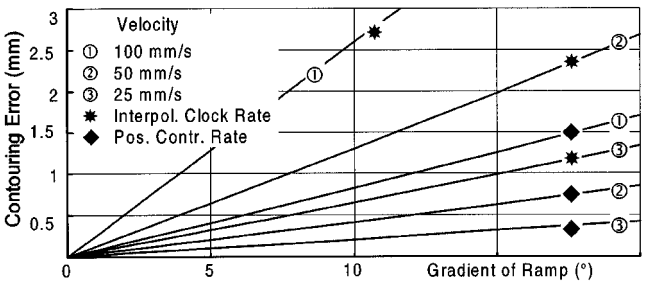


Fig. 9. Contouring Error of Sensor Control Loops.

the time-delay. But this is restricted by the necessary calculation time for the path planning of the robot control.

The dead beat controller used, clearly reduces the rise time of the sensor control loop. But it is still 2.5 times higher than the rise time with a PI-controller at the position control clock rate.

The effect of time-delay of the controlled systems can be especially recognized with an amplitude-log frequency curve and a phase frequency response. The second one indicates the high phase reducing effect of the time-delay of the controlled system at the interpolation clock rate. Compared with a sensor control loop at the position control clock rate, the fast reduction of the phase characterizes a higher contouring error, if the robot should follow a given contour. The increase of the contouring error becomes clearly, when considering the 3.2 times bigger Kv-parameter of the sensor control loop at the interpolation clock rate.

Figure 9 gives an overview of the resulting contouring errors of the sensor controlled systems at the interpolation and the position control clock rate. The contouring error is an essential criterion for deciding whether or not a task can be solved by sensor control loops. The demands of various material processing technologies, concerning the path velocity and the path accuracy, are presented in Table II and are compared to the characteristics of sensor control loops. The path velocity and accuracy given in Table II are typical values of the considered material processing technologies.[5]

Finally, in Table III the essential characteristics of the sensor control loops at the interpolation and the position control clock rate are summarized.

The advantages of sensor control loops within the position control clock rate are decreased with the disadvantage of higher expenditure for calculating the manipulated variables for the robot control. Formerly, the necessary computation of the kinematics and the inverse kinematics of the robot required a higher investment for a transputer network. This disadvantage has been reduced within the last years, because high performance processors are available. Summarizing, it can be said that sensor control loops within the position control clock rate possess the highest development potential.

5. APPLICATIONS

The developed sensor control loops are used for applications in the field of three-dimensional laser material processing. There, it is very important that a constant distance between the nozzle and the workpiece is always kept to guarantee a high product quality. Distance control

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Table II. Characteristics of Applications and Sensor Control Loops.

Applications	Path Velocity (m/min)	Accuracy (mm)	Sensor Control (IPO): max. Gradient (°)	Sensor Control (IPO): max. Gradient: x = 50mm	Sensor Control (Pos. Contr): max. Gradient (°)	Sensor Control (Pos. Contr.): max. Gradient: x = 50mm
Laser Cutting	1–15	0.2	4.7–0.3	4–0.3	14.4–1.0	13–0.9
Laser Welding	1–6	0.2	4.7–0.8	4–0.7	14.4–2.5	13–2.1
Laser Bending	1–10	0.2	4.7–0.5	4–0.4	14.4–1.5	13–1.3
Arc Welding	0.5–3	0.8	33.1–6.2	32.6–5.4	64.0–18.9	102.7–17.1
Gluing	10–30	0.7	1.6–0.5	1.4–0.5	5.1–1.7	4.5–1.5
Deburring of Plastics	5–15	0.5	2.3–0.8	2.0–0.7	7.3–2.5	6.4–2.1
Deburring of Ceramics	0.1–1	0.3	50.7–7.0	61.1–6.1	75.4–21.1	192.6–19.3

Table III. Comparison of various characteristics of Sensor Control Loops.

	Interpolation clock rate (Dead Beat Controller	Position Control Rate (PI-Controller)
Rise Time of the Controlled System (ms)	190	65
Rise Time of the Control Loop (ms)	172	70
Kv-Factor (1/s)	6.79	21.4
Countouring Error, Gradient = 19.5°, Path Velocity = 90mm/s (mm)	4.8	1.5
Frequency with Phase = − 45° (Hz)	0.87	4.2

loops are absolutely necessary for such applications. The distance is measured with a capacitive sensor integrated in the nozzle. At high path velocity the control loop must possess high dynamic characteristics. Sensor control loops within the position control clock and a commonly used PI-controller fulfil this requirement. In combination with an additional axis, fixed on the last robot axis, the sensor control loop could be used to keep the additional axis in an optimal working point. Thereby, the small range of the additional axis could be enhanced. This essentially simplifies the teach-in programming.

Within the field of laser welding the sensor control loops are applied for seam tracking. The used sensor is a laser scanner. The sensor principle is based on the laser triangulation and provides the position of the welding seam. This information makes it possible to control the path of the robot and the orientation of the sensor.

6. CONCLUSION

According to various demands of material processing technologies, concepts for integrating sensor data into industrial robot controls were developed. Thus, a powerful and configurable sensor-robot-system was designed and implemented, consisting of an advanced commercial robot control, a plug-in Single-Board-PC and various sensors.

To design efficient controllers the controlled systems were identified with step functions, within the interpolation or at the position control clock rate. Based on this, a model of the system was established and optimized. Different controllers were designed and the system responses of the control loop were simulated and optimized by an efficient control design tool.

Experimental results on the achievable sensor controlled path accuracy, relative to given path velocities and workpiece contour errors, are presented. Finally, some applications were introduced to demonstrate the usage of the control loops.

ACKNOWLEDGEMENT

The authors wish to thank the Bayerische Forschungstiftung (FORLAS) for funding parts of the work presented here.

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