

# A DISTRIBUTED FAULT TOLERANT POSITION CONTROL SYSTEM FOR A BOAT-LIKE INSPECTION ROBOT

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Abstract: Here we present the position control system of a swimming inspection robot for large under-ground concrete pipes that are partially filled with wastewater. The system consists of a laser-based measurement subsystem for position determination and a mechanical rudder to move the robot laterally within the pipe. The required software components are implemented as services following a CORBA-based architecture. To automatically adapt the position control system to different environment conditions, a self-tuning controller is used. The controller has hybrid requirements regarding latency and interarrival times of computed position values. In this contribution, we describe the architectural support for this application as well as how the system deals with excessive latencies due to transient overload.

## 1 INTRODUCTION

The Emscher genossenschaft based in Germany is currently planning the Emscher sewer system, arguably the largest residential water management project in Europe in years to come. The new emscher sewer will show a total length of 51 km and diameters between 1.4 and 2.8 m in depths up to 40 m under surface. The Emscher genossenschaft engaged the Fraunhofer Institute for Factory Operation and Automation (IFF) in Magdeburg, Germany, as the general contractor to develop automatic inspection and cleaning systems to meet the requirements imposed by legal guidelines.

Large under-ground concrete pipes that are partially filled with wastewater are a hazardous environment for man. Nevertheless, inspection of such pipes must be performed on a regular basis. Many of today's remote controlled inspection systems for underground sewer pipes consist of a single TV-camera and are designed for pipe diameters below one meter. The recent development of automatic inspection systems (Elkmann et al., 2005) equipped with advanced sensors makes it possible for an operator to perform this task from an outside position even for pipes with a diameter between 1.4 to 2.8 meters. The cable-guided damage surveying system (SEK) (see Fig. 1) was developed to be a versatile

and easy-to-use tool to detect various kinds of damages above and underneath the water-line with high accuracy.

The inspection process is largely automated (Elkmann et al., 2006) and supervised by an operator from within a service-vehicle outside of the sewer. To ensure an optimal inspection result the system must acquire data from a centered position.



Figure 1: The cable-guided damage surveying system within a sewer pipe.

For this reason, it is our goal to keep the robot near the center of the pipe during the data acquisition phase. We must also deal with different environment conditions. These include water level, flow velocity and pipe diameter. A traditional controller with fixed parameter set was unable to maintain a stable posi-

tion depending on the current conditions. To tackle this problem the position control system of the robot was fitted with a self-tuning controller that is able to identify model based control parameters prior to data acquisition.

The main part of the controller was implemented using a software programmable logic controller (PLC). The input to the controller is the current lateral position relative to the pipe axis. An iterative algorithm using data from various sensors, mainly three banks of laser distance sensors, determines the position. The PC-based implementation of this algorithm has an unknown worst-case execution time (WCET). The actual execution time is depending on the internal state of the software as well as on the current input data. Further delay stems from the transmission of data over the Ethernet network between PLC and PC as well as from the scheduling scheme of the calculation task. While the actual controller is robust against certain latency and jitter of the arrival of position data, we must consider cases when position data does not arrive in time. This may happen due to unusual long execution time of the position determination algorithm or due to transient overload of the communication channel.

Another challenge is the second part of the self-tuning controller, which performs the identification of the system's behavior and which derives an adequate control parameter set. The algorithm used here is very sensitive to jitter of the interarrival times of position measurements and to missing samples.

An architectural approach for solving both problems is described in section 3. In section 4, the actual controller is presented in more detail. Section 5 briefly discusses the dynamic quality of service approach used to avoid failure in case of transient overload.

## 2 RELATED WORK

Realizing time critical applications using complex distributed systems is a challenging task. On one hand, considerable work has been done to introduce time constraints or timely predictable behavior. On the other hand, a number of approaches have been published to relax time constraints of certain applications by introducing fault tolerance mechanisms.

In the field of communication middleware, the Object Management Group (OMG) has released extensions to the known CORBA-specification to extend it with real-time features (Wolfe et al., 1997). The primary focus here is on the introduction of priorities when executing method calls, which re-

quires appropriate system software support. Software libraries implementing this standard were also made available (Schmidt et al., 1998).

To relax time constraints, approaches that try to balance quality of service and required computation time were considered. This includes the classical "anytime" (Dean, Boddy, 1988) or "flexible" (Hendler, 1989) algorithms, where quality of service can be dynamically traded against shorter computation times. This scheme can be used to ensure the timeliness of computations. The authors of (Nett et al., 1998) have also dealt with meeting task deadlines. They use a dynamic task scheduling scheme with detection and handling of timing faults. Faults are handled via a task-pair strategy with invocation of an alternative exception task in case of a timing fault.

## 3 DATA ACQUISITION AND PROCESSING

### 3.1 Modeling Data Flow using Services

We developed a service oriented CORBA-based software architecture focusing on data flow and distributed processing. In our system, an application is constructed by combining software modules that provide functionality to other modules via a generic interface. The modules may be arbitrarily distributed over a number of computers in a network. The interface of the services is data centric. It allows services to offer data via named buffers to other services or clients. Each buffer represents a time series of specific data objects (see Fig. 2). A service can represent a data source (e.g. a sensor), a processing module or a data consumer (e.g. an actuator, a database, or a GUI). Services that represent sensors or sensor systems may provide data that represents a single measurement, a time series of measurements, a vector, an image, or any other types of data that are generated by the sensor system. Other services may not provide sensor data but processing results.

By connecting the services via the publish/subscribe paradigm the data flow of the application is modeled. In this communication model, the services play different roles. The module providing data is called the service provider. The data consumer is called the service client. Please note that in our system a client does not subscribe to specific data elements but to notifications on when such elements become available.

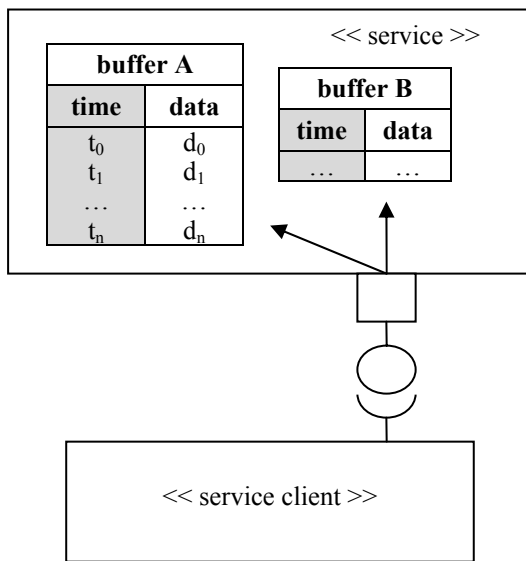


Figure 2: A service provider offers data buffers to clients via a generic interface.

The data objects that are being exchanged between services satisfy a given scheme. They consist of binary data and metadata in XML syntax. The most important element of the metadata is the timestamp, which indicates the recording time of the original data. The timestamp acts as a key for the data object within the given data buffer. The binary data can contain information in any format. A client can request individual data elements or arbitrary blocks of data elements from a buffer. This is achieved by sending structured queries with a simple syntax to the accordant service. The client can then process these data items and/or eventually offer the results to further clients. The foundation of the used timestamps is the Newtonian time model. Timestamps are generated based on synchronized local clocks. A simple clock synchronization is carried out via the network by a dedicated service. The accuracy of synchronization between time-server and any client is better than 100  $\mu$ s. This is well below the shortest interarrival times of data elements in our application. It was achieved using common PC-hardware, Giga-bit-Ethernet, and a Windows NT-based operating system. Accuracy may be improved by using more sophisticated clock synchronization algorithms.

### 3.2 Implementation of Position Determination

Determining the position of the robot is of great importance. Knowledge of the position is not only required for position control, but also to process and

interpret other sensors' data. This includes the registration of images from a high-resolution photographic camera system, the analysis of data from an ultrasonic underwater scanner, the determination of the magnitude of corrosion and incrustations, or the precise measurement of possible deviation of the position of individual pipe segments. These tasks cannot be performed without knowledge of the pose of each sensor during data acquisition.

The heart of the position determination subsystem is an algorithm that was specifically developed for this purpose. It is implemented as a service (the position determination service; PDS). It is based on the measurements of a number of laser ranging sensors plus an inclination sensor. A discussion of the exact procedure can be found in (Elkmann et al., 2006).

Measurements from the laser sensors are acquired by the onboard PLC. The PLC is implemented in software on an embedded PC and tightly coupled with an interface service (IS). The IS has access to the PLC's memory and is configured to insert time-stamped measurements into a buffer queue at a rate of 100 Hz. This rate is consistent with sensor capabilities and sufficient for our application.

The PDS is notified of the arrival of new data elements in the IS's buffer. Its goal is to process all data elements that are produced by the IS. To do this the PDS uses the following strategy of data access: Upon notification of a new data element, it asks the IS for all elements that succeed the last element the PDS has already processed. This is done via a single "get"-operation. By using this technique, it is possible for the PDS to catch up in case of a previous transient overload. For each received data element, the system's position is calculated and eventually made available for further processing by other clients.

## 4 SELF-TUNING CONTROLLER

### 4.1 Controller Design

One challenge in the context of stable data acquisition between real time and non-real time systems (hybrid systems) is the implementation of non-linear controllers. This chapter describes the motivation of using a non-linear controller in this area. In addition, it gives a short introduction of calculating them.

When travelling through a partially filled sewer, the position of the SEK is controlled by a rudder arm mounted on top of the robot. The rudder can be

turned relative to the longitudinal axis of the pipe. In turn, buoyancy forces the SEK to change its position. Due to disturbances, a controller has to be integrated for closed-loop navigation. Self-tuning controllers belong to the denomination of adaptive controllers. They are used to fit the plant on a variable environment. In fact, the flow velocity of the wastewater, the water level, and the pipe diameter may change depending on the actual sewer and on current conditions like the time of day or the weather situation. This motivates to use adaptive controllers for the robot. The benefit of adaptive controllers compared to fixed structure designs is the broad field of applications. Here we will focus on the self-tuning controller as a substitute of indirect adaptive controllers.

Intermediate instances are required for the calculation of the controller parameters (see Fig. 3).

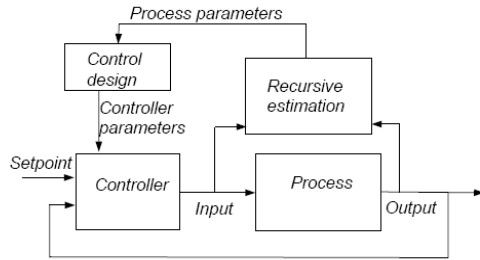


Figure 3: Schematic diagram of a self-tuning controller.

The calculation of a self-tuning controller contains the following steps:

- Recursive estimation of process parameters (system identification)
- Suitable determination of a control law with adjustable parameters
- Calculation of controller parameters based on the desired closed-loop system
- Update the parameters using the IS

The advantage of this method comprises the possibility to secure each step of calculation before the controller parameters are used. In addition, the closed loop can be pushed to a desired behavior while the parameters of the plant are changing.

The plant is depicted by a discrete autoregressive moving average with an extra input model (ARMAX-Model) of fourth-order. The advantage of ARMAX-Models compared to simpler models is the adequate freedom in describing the properties of the disturbance term.

That gives the model:

$$y(t) + a_1y(t-1) + \dots + a_3y(t-3) = b_1u(t-1) + \dots + b_3u(t-3) + c_1e(t) + \dots + c_3e(t-3) \quad (1)$$

with

$$\theta = [a_1 \dots a_3 \quad b_1 \dots b_3 \quad c_1 \dots c_3] \quad (2)$$

where  $y(t)$  is the plant output,  $u(t)$  is the control input and  $e(t)$  the prediction error. In this case, the least-squares criterion:

$$V(t) = \frac{1}{t} \sum_{i=1}^t \lambda^{t-i} (y(i) - \varphi^T(i)\theta)^2 \quad (3)$$

is being used to identify the transmission behavior of the process. The parameters are time varying in a small range during operation. Hence, it is desirable to base the identification on the most recent data rather than on the older data. This can be achieved by exponential discounting ( $\lambda$ ) of old data. Then, it can be shown (Lennard Ljung, 1999) that the extended recursive least square scheme (ERLS) becomes:

$$\theta(t) = \theta(t-1) + L(t)[y(t) - \varphi^T(t)\theta(t-1)]$$

$$L(t) = \frac{P(t-1)\varphi(t)}{(\lambda + \varphi^T(t)P(t-1)\varphi(t))} \quad (4)$$

$$P(t) = \frac{1}{\lambda} \left( P(t-1) - \frac{P(t-1)\varphi^T(t)P(t-1)}{\lambda + \varphi^T(t)P(t-1)\varphi(t)} \right)$$

Using ERLS it is advisable to consider the persistent excitation in view of convergence of the parameter estimation. In this step, the indirect method permits to prove the estimated process parameters on separate recorded test series. If the verification is successful, the calculation of the controller parameter is performed.

Fig. 4 depicts exemplary the change of positions predicted by a calculated model towards measured data. The rudder angle as input to the ERLS was oscillating between minus five and five degrees. The calculated model is afterwards the starting point for the controller design.

The idea regarding the controller design is to compensate the plant with the inverse system and a desired transmission behavior.

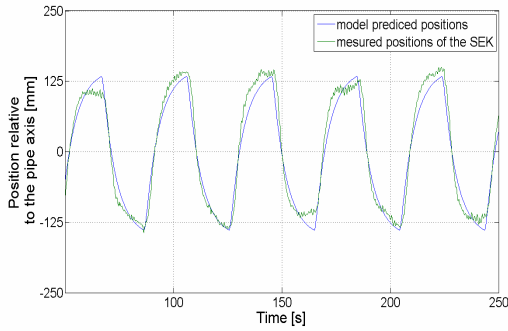


Figure 4: Measured and predicted positions of the SEK.

Assuming that the desired close loop behavior as shown in equation 5 where  $z^{-1}$  is backward shift operator.

$$M(z^{-1}) = \frac{\hat{B}(z^{-1})}{\hat{A}(z^{-1})} \quad (5)$$

The actual closed loop is:

$$G(z^{-1}) = \frac{K(z^{-1})S(z^{-1})}{1 + K(z^{-1})S(z^{-1})} \quad (6)$$

with the controller:

$$K(z^{-1}) = \frac{D(z^{-1})}{C(z^{-1})} \quad (7)$$

and the plant behavior:

$$S(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} \quad (8)$$

The suitable controller law is then given by equation 9 without solving a Diophantine equation.

$$\begin{aligned} D(z^{-1}) &= A(z^{-1})\hat{B}(z^{-1}) \\ C(z^{-1}) &= B(z^{-1})(\hat{A}(z^{-1}) - \hat{B}(z^{-1})) \end{aligned} \quad (9)$$

In terms of the causality of the controller law, we get the following conditions for the implementation:

- The transmission behavior of the plant has to be stable, respect to the inverse implementation in the controller law.
- The polynomial of the decoupled model  $\hat{A}(z^{-1}) - \hat{B}(z^{-1})$  should only have zeros within the unit circle.
- The estimated plant model should not include a minimum phase system or must be corrected because of the stability of the open loop.

- The controller law has to be causal.

The calculated controller is therefore less sensitive to noise compared to other designs like the pole placement variant, which is described by (Aström, Wittenmark, 1992).

## 4.2 Implementation

The self-tuning controller was implemented in the form of two main modules. The first module is the actual controller. It runs as a real-time task within the onboard PLC. Position-data is fed into it by the IS as described in section 3.2. The IS acts also as a client similar to the PDS but with a different strategy of data access: The controller doesn't want to process all data elements that are produced by the PDS, but needs the most recent one. For this reason the IS upon notification of new data requests the most recent data element from the PDS and feeds it into the PLC.

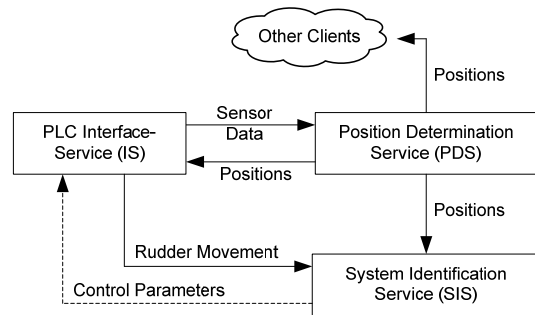


Figure 5: Structure and data flow of controller implementation.

The second module is a service, which computes the control parameter set (system identification service; SIS). It needs two kinds of data elements as input: (1) all sampled rudder arm angles during the system identification process and (2) the corresponding system position. The arrival of these data is not time critical but it is necessary that all samples are being processed. It therefore uses a similar data access strategy as the PDS to gather all data elements that describe the rudder movement from the IS. Furthermore, it requests for each such element the two closest system positions from the PDS and interpolates between them to get the corresponding system position. Requesting closest elements given a certain timestamp is another feature of the data-access mechanism of our architecture. After the SIS has collected enough data, it can compute the control parameters and send them to the main control module via the IS. The described data flow is shown in Fig. 5.

## 5 DYNAMIC QUALITY OF SERVICE

Even though we have successfully implemented the system identification part of the controller as a non-real-time service while guarantying the required data quality, the actual controller may still suffer from excessive latencies in the arrival of position data from the PDS. This is because of (1) the iterative algorithm used in the PDS and (2) because of large latencies in the communication between the distributed services due to transient overload of the communication channel.

To avoid system failure in such cases we integrated a dynamic quality of service approach that uses the timestamps of the position data available to the controller implemented in the PLC to determine the age of that data. If a certain age is exceeded, the controller uses an alternative position that it computes by a simple prediction mechanism based on the last known positions. This fall back mechanism is triggered if the position data available to the PLC becomes older than 90 ms. While this is a crude method and could easily be improved by using a more accurate model based approach, it is sufficient to deal with short disruptions of communication. If however the position data becomes older than 900 ms, the controller is put into a safe state. In this state, the rudder is moved into centered position, which is the state that most unlikely causes a collision with the wall. The controller resumes as soon as position data not older than 90 ms becomes available again.

We performed experiments with a prototypic implementation of the system under operating conditions. To determine the actual interarrival times of data produced by the PDS, we used a test-client that was consuming position data in the same way as the IS. In Fig. 6, the interarrival times recorded by the test-service are shown. Well under 5 percent of the position values arrived slightly later than usual. Less than 1 percent of that were delayed more than 90 ms. When that happened, approximately 50 percent were delayed more than 900 ms.

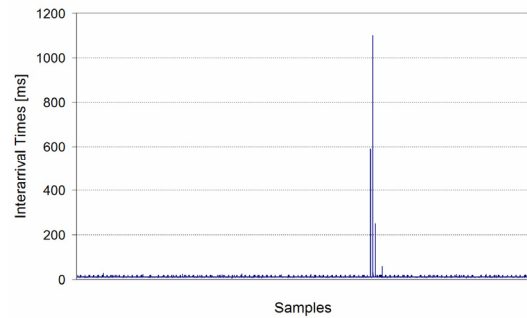


Figure 6: Interarrival times of position data at Test-Service.

When observing the behavior of the robot during the experiment, no significant deviation from the ideal position could be noticed. The system maintained position near the center of the pipe when missing the 90 ms deadline. This was also the case when briefly missing the 900 ms deadline. This can be attributed to the fact that we only had small turbulences that required only slight corrections by the position control system. However, we expect that missing the 900 ms deadline may have a significant effect in case of more severe turbulences.

## 6 CONCLUSIONS

Here we presented an application of a distributed control system for position control of a boat-like inspection robot for partially filled sewer pipes. We discussed the hybrid requirements of an advanced self-tuning controller regarding timeliness and interarrival times of its input data. We presented a scheme for detecting and handling excessive time delays to prevent system failure by using dynamically reduced quality of the position controller. It was also discussed, how the controller was integrated into a non-real-time service oriented software system. We conclude that in case of our application it is feasible to use soft- or non-real-time components in the control loop. Prerequisites are (1) a deterministic data acquisition with time stamping and (2) a hard-real-time controller core with fault tolerance mechanisms.

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