A Smart Milling Fixture Controlled by Distributed RTLinux

Mario Schüpany, Markus Gusenbauer and Ingomar Müller
Profactor Produktionsforschungs GmbH
Im Stadtgut A2,
4407 Steyr-Gleink,
Austria
{mario.schuepany,markus.gusenbauer,ingomar.mueller}@profactor.at

Abstract

A vast need of current production industry is a significant increase of manufacturing precision and quality. A major step towards accomplishing these needs is MESACTIF (Modular Embedded System for ACTive Intelligent Fixtures), a fixture mounted underneath conventional part fixtures of milling machines. The goal is to significantly enhance the machine's accuracy and to enable the innovative manufacturing of complex shapes. A special requirement is modularity at all design levels to ensure high adaptability for a wide range of possible future applications. The result is a mechatronic system based on a RTLinux distributed embedded system.

1 Introduction

This paper deals with the development of active intelligent fixtures within the scope of the research project MESACTIF [1]. The technical goal is to develop an innovative embedded micro-positioning device, mounted underneath conventional part fixtures, for the generic micro-machining of parts and the machining of complex shapes.

The flexible and adaptive control concept which is going to be developed, meets the challenges which are intrinsic to machining tasks: high dynamics and forces, highest requirements on precision and coupled kinematics with complex motions. The modular sensor-actuator concept finds its match in a modular distributed control scheme of embedded controllers where each embedded system controls a lower-dimensional sensor-actuator system.

2 Motivation

Current and future precision-machining applications vary widely in requirements concerning precision, flexibility, dynamics, forces and degrees of freedom (= DOFs). To provide modular solutions for a great variety of these applications, embedded design becomes imperative.

The presented development of active intelligent fixtures can stimulate the future trend in micro-machining by allowing precision cutting and the compensation of process-related vibrations. Arrays of simple embedded sensor-actuators that can perform complex coordinated motions also open up new applications in vibration suppression. Furthermore, with proceeding miniaturization of embedded sensors, actuators and controllers, the proposed embedded system can even pioneer ”medium-scale sensor-actuator arrays” which are considered as one of the most promising technologies for new potential applications in robotics, aerospace, or flexible structures [2].

3 Active Intelligent Fixtures

Modularity is one of the main goals in both, the sensor-actuator system and the embedded control system. Modularity can be achieved at many levels such as software, hardware, or in various combinations. The approach of using decentralized embedded systems even in ultra-dependable applications is a logical consequence of going a step farther. A distributed system consists of a set of embedded units and a communication network interconnecting these units. Depending on the application, various forms of communication between embedded units are available. In the automation area, field buses such as PROFIBUS or CAN-bus are common. For safety-critical real-time applications, such as X-by-wire, Time Triggered Technology (TTT) is setting a standard. For less safety-critical but bandwidth-demanding applications, Ethernet, USB, USB2 and IEEE1394 buses are new, inexpensive alternatives.

Distributed control is advantageous if spatially distributed embedded units require rapid response times or computational power exceeding available communication bandwidth or the performance of single board controllers. Furthermore, distributed control supports modular design concepts for building smart systems or sub-systems of interconnected smart devices, such as in cars, with motor-control, ESP, and many more.

Embedded sensor-actuator systems represent an enabling technology with growing scientific and technological importance. Vibration control, static and dynamic shape control and micro-positioning represent only some of the possible application domains. A comprehensive survey on vibration and shape control with embedded smart materials is given in [3].

In general, actuation in embedded micro-positioning systems is realized with multi-layer piezoelectric devices due to their high stiffness as well as dynamic and energy density. Technical systems integrate several piezoelectric elements up to large-scale arrays comprising hundreds of piezoelectric sensors and actuators. Bendable piezoelectric polymer foils are upcoming alternatives for sensors, but do not show sufficient power for actuator usage compared to ceramic patches and piezoelectric stack actuators. Piezoelectric devices might gain even more importance with upcoming availability of bendable piezoelectric ceramic-polymer composite foils [4].

Demands on applications for high- and ultra-precision machining of mechanical parts are increasing in recent years, especially in semiconductor, computer and electronics industries. Modern high efficiency tools, especially in the field of micro- and precision-machining, target at solving the challenge of chip removal with highest flexibility and process security. Besides the detailed knowledge about tools, process and material to tune the process, the possibility to change important parameters during the process with the help of micro actuators gains increasing importance. Currently, precision- and micro-machining is carried out with specialized, low throughput tooling machines, making cost efficient highest-precision mass production impossible.

4 Technical Solution

The overall ACTIF (= ACTive Intelligent Fixture) is a mechatronic system with several technical challenges in design of the embedded control structure, the control algorithms, the positioning device and the power electronics.

To meet the requirement of modularity mentioned in section 3, the embedded control structure is being split into autonomous parts, which are linked together by the communication system.

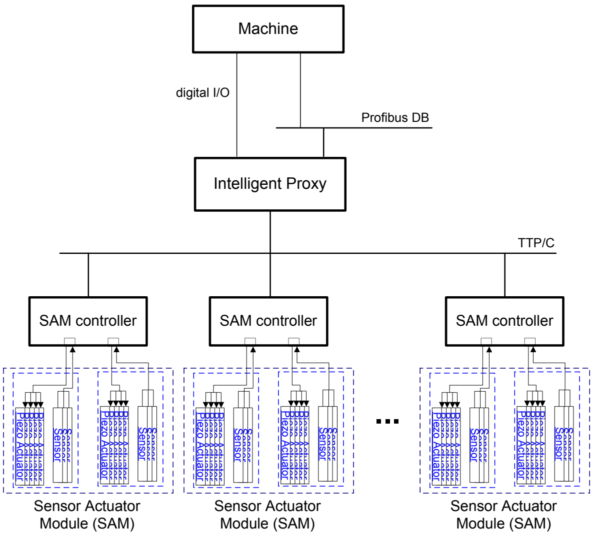

FIGURE 1: *Overview of the micro positioning system.*

The main parts of the MESACTIF system are the Intelligent Proxy(IP), the mechanical part of the system called Sensor Actuator Module (=SAM) and the controller(s) for a SAM (=SAM controller) as shown in figure 1. The following subsections describe the parts of the system in more detail.

4.1 Sensor Actuator Module

Depending on the required DOF and the complexity of the application's workpiece motion, an ACTIF can consist of one or several Sensor Actuator Modules (= SAMs). While simple tasks can be efficiently performed with a single SAM, complex and spatial motions of the workpiece are achieved by the kinematic coupling of multiple SAMs.

One SAM is controlled by two SAM controllers in the case of 3-6 DOF, whereas 1 and 2 DOF motions are possible with only one embedded controller. The number of SAM controllers per SAM depends on the number of I/Os and the processing power needed by the control algorithm. A SAM itself is split into several Sensor Actuator Arrays (=SAA) where one array consists of two piezo stacks acting as actuators and one eddy current sensor. Depending on the required forces normally one or two SAAs are used per DOF. For the current prototype shown in figure 2 we build a 3 DOF system with 8 SAAs.

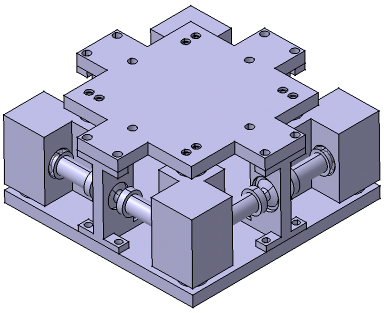

FIGURE 2: *Prototype of a Sensor Actuator Module.*

The piezo stacks in use are off-the-shelf products. The advantages of piezos are the high possible motion frequencies and the high accuracy in positioning. A drawback, normally, are the low forces which can be handled by a piezo. This was one of the challenges in construction to overcome this weakness.

Each piezo is driven by a power amplifier of about 60 watt. The SAM controllers are connected via the control inputs of the amplifiers to the SAMs. It is the task of the SAM controllers to control the motions of the SAM. See the next sections for more details.

4.2 SAM controller

The controller, which is responsible for the control of the SAM is called SAM controller (=SAMC). They are connected via a real-time communication bus to an Intelligent Proxy (= IP) which is itself responsible for the communication with the machining centers' controller. For more details about the IP see section 4.3.

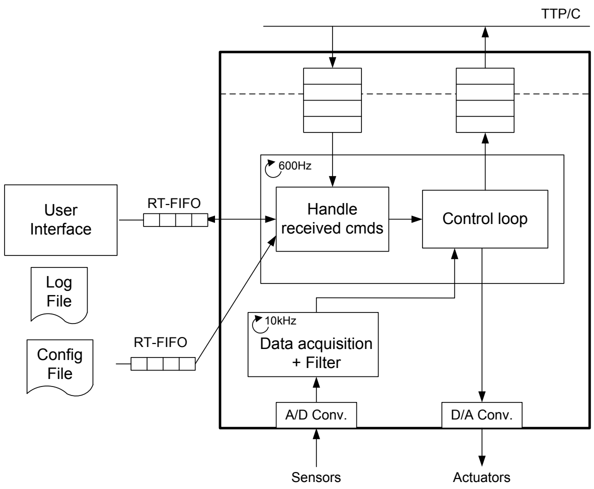

FIGURE 3: *Sensor Actuator Module controller*

As can be seen in figure 3, the motion commands are sent via a bus (see section 4.4) to the SAMC. For testing purposes, the motion commands can also be sent via a simple ASCII user interface which use shared memory and a real-time FIFO for communication. Depending on the source of motion the command is preprocessed and the according control value is sent to the control loop. The control loop acquires the data of the SAAs from a 16bit A/D converter and drives a 10 bit D/A converter with the control signal for the piezo power amplifiers.

The used control algorithm is based on a sliding mode control concept [5], which is suitable for our needs in terms of high robustness and low processing complexity. The objective of the controller is to reduce positioning errors and to force the actuators to follow the commanded trajectory with minimum tracking error. The required feedback and feedforward terms as well as a disturbance observer are obtained in the derived control law. In addition, the controller stability is guaranteed through the application of the Lyapunov stability theorem.

At startup of the SAMC a configuration file is read, which describes the possible motion space of the controller. For documentation and validation purposes, the controller writes the results into a log file which can be used for post processing.

The next section describes the Intelligent Proxy in more detail.

4.3 Intelligent Proxy

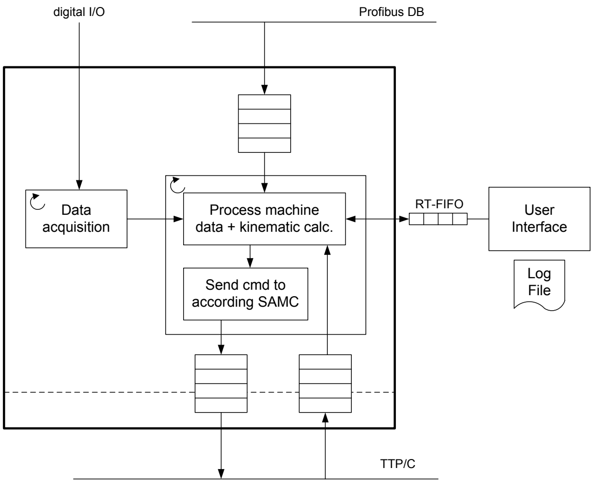

FIGURE 4: *Intelligent Proxy*

As already mentioned in section 3 the Intelligent Proxy (IP) realizes the connection between the machining centers' controller and the variable number of SAMC. Its task is to process the incoming data from the milling machine, to calculate the kinematics, to decide which SAM is appropriate to the desired motion and to send the motion command to the according SAMC. See figure 4 for a system overview.

The connection to the milling machine is realized with Profibus. The milling machine acts as the master and the ACTIF as the slave. Special focus was on the seamless integration to ensure a similar behavior like other comparable milling machine extensions.

For test and validation purposes an ASCII user interface with a simple logging mechanism was implemented.

The connection between the IP and the SAMCs requires a real-time communication system, which is described in the next section.

4.4 Communication System

The design of the embedded control structure is highly influenced by the communication network. We decided to choose a time- triggered architecture (= TTA)[6] instead of an event-based one because of the high composability in respect of time in TTA systems. The unmatched dependability and RT-properties of the TTA are imperative since acceleration-, speed- and force requirements of MESACTIF systems are based on over-determined, antagonistic SAMs that must be controlled. Temporal properties between all controllers can be fully defined at design time, thus eliminating indeterminate system behavior due to temporal jitter, latencies, collisions and other non predictable behavior.

Figure 5 shows the structure of a typical TTP/C bus to which several embedded systems are connected. The embedded systems within a TTA system offer a data sharing interface without any control signals crossing this interface. The data transport from senders to receivers occurs on predetermined points in time which are stored in scheduling tables. This supports modularity in a real natural way. It is the task of the designer to fit the subsystems into the entire application.

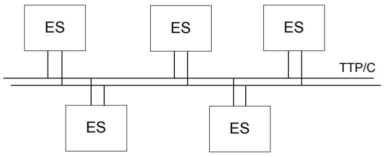

FIGURE 5: *Bus topology of TTP/C*

5 Controller Hardware

The controller hardware is based on PC/104 platforms with a Pentium I 166MHz with 64 MB RAM. As data storage an ordinary hard disk was used. The footprint of the installed embedded systems is about 7 MB. For the IP a PC/104 Profibus interface card from Hilscher is used. A digital I/O card offers future extendability to acquire additional process relevant data from the milling machine. The SAM controllers are equipped with 16 bit A/D and 10 bit D/A channels from Diamond Systems. They offer 8 differential A/D inputs and 10 D/A outputs. The main reason for choosing PC/104 was the high extendability, the great availability of peripheral cards and the reasonable costs. The test equipment consisting of one IP and two SAM controller was integrated into a 19" rack due to transportability reasons and the rough industrial environment.

The host cross development environment is based on cygwin [7] and gcc. The embedded Linux controllers use Busybox and TinyLogin (see [8] and [9] for more information on the set-up of embedded Linux systems). The kernel is patched with GPL RTLinux 3.1.

6 Results

A prototype system with one SAM, two SAM controllers and one IP has been tested so far in the lab. The first results are promising, since the ACTIF has improved the accuracy of the whole system by a factor of 10.

The use of a time-triggered architecture enabled the independent development of the embedded subsystems and the communication protocol. Especially the predefinition of the communication timing behavior reduced the deterministic data exchange to the well known shared memory exchange. Thus the implementation of each embedded subsystem was possible without uncertainty in respect of time.

The implementation of all embedded systems follows the idea of [10] for a real-time part and a non real-time user interface which communicates with the real-time part via shared memory and real-time FIFOs. It turned out that this structure forms a good basis for control applications and covers the standard needs of embedded real-time applications like user input for test purposes, monitoring and logging.

7 Conclusion and Future Work

From a technical point of view, the actual number of SAM controllers - coordinated by the IP - is only restricted by the bandwidth of the communication network and the CPU power of the IP. In future applications a hierarchical IP structure with embedded controllers for every IP will further improve system performance.

The project MESACTIF opens the door to new applications in manufacturing that allow cost-efficient production of components with an innovative mechanical design. Embedded systems technology used in MESACTIF, pioneers control of medium-scale sensor-actuator arrays and thus will allow e.g. dynamic vibration control of critical systems and components in stationary and non-stationary applications.

8 Acknowledgment

The current research project MESACTIF is funded by the Austrian Federal Ministry of Transport, Innovation and Technology within the support program FIT-IT, which is gratefully acknowledged.

References

[1] *www.mesactif.org*, accessed Sept. 30, 2004.

[2] Douglass B., 2002 *Trends in Real-Time and Embedded Systems Development*,Internal Report Hugo Fierz Züricher Hochschule Winterthur CH.

[3] Irschik H., *A review on static and dynamic shape control of structures by piezoelectric actuation*, pp 5-11, Elsevier, 2002.

[4] M. Sunar and S. S. Rao, 1999, *Recent Advances in Sensing and Control of Flexible Structures via Piezoelectric Materials Technology*, ASME Applied Mechanics Reviews, Vol. 52, pp1–16.

[5] Edwards Ch. and Spurgeon S. K., 1998, *Sliding Mode Control*, Taylor & Francis Ltd., ISBN 0-7484-0601-8.

[6] Kopetz H., 1997, *Real-Time Systems: Design Principles for Distributed Embedded Applications*, Kluwer Academic Publisher, ISBN 0-7923-9894-7.

[7] *www.cygwin.com*, accessed Sept. 30, 2004.

[8] Yaghmour K., 2003, *Building Embedded Linux Systems*, O'Reilly, ISBN 0-596-00222-X.

[9] *www.nanotech.wisc.edu/ khan/software/gnu-win32/cygwin-to-linux-cross-howto.txt*, accessed Sept. 30, 2004.

[10] Wurmsdobler P., Vienna 1999, *A simple control application with Real Time Linux*, In Proceedings of the 1st Real-Time Linux Workshop.