SMART MACHINE SUPERVISORY SYSTEM: CONCEPT, DEFINITION AND APPLICATION

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Abstract: In today’s competitive world, manufacturers have realized that they need to embrace automation as their mantra to success. However, the impact of automation primarily concerns with the effectiveness of process monitoring and control systems. There is a need for a closed loop supervisory system, which integrates and coordinates individual process modules for real-time adjustment, conflict resolution and priority assignment. Monitoring and control of multiple process modules will result in higher productivity, better quality and prognostics for near-zero breakdown performance.

In this paper, we define the supervisory system as open architecture system that integrates and coordinates individual process monitoring and control modules such that a real-time globally optimal machining solution is delivered for maximum productivity. The Smart Machine Platform Initiative (SMPI) is currently being managed by TechSolve in support with Coalition on Manufacturing Technology Infrastructure. SMPI efforts at TechSolve concentrate on six thrust areas including the supervisory system. We then proceed to explain the technical and functional requirements, benefits and architectural details with emphasis on the knowledge system. A prototype supervisory system application is explained with objectives, setup, technologies identified and results.

We conclude with further insights into issues and implications for successful realization of a smart machine supervisory system.

Key Words: Centralized Control; Globally Optimum Solution; Process Co-ordination; Process Monitoring and Control; Supervisory System
1. Introduction

Traditional manufacturing took a giant step forward in 1950’s with introduction of Numerically Controlled (NC) machine tools. The advent of NC into the manufacturing world had paved the way to machine large batches of components without compromise on product quality and process efficiency. A next significant development in machine tool automation was the introduction of Computer Numerical Control (CNC) in the early 1970’s where a dedicated computer replaced most of the electronic hardware and punch cards of the NC machines [5]. The ease that CNC brought to the machining world can best be illustrated with the far-reaching transformations like faster, smoother and easier machining of curves, complex 3-dimensional profiles, etc. The transformations were so comprehensive across the manufacturing world which soon witnessed the development of powerful software tools to aid in the manufacturing process, that soon grew into our present day Computer Aided Manufacturing (CAM), Computer Aided Design (CAD) and Computer Aided Engineering (CAE) tools.

As the requirement for parts with tighter tolerances mounted up, it was inevitable that CNC machines were ushered into a new manufacturing world. The dawn of CAD, CAM and CAE in the manufacturing world triggered a plethora of various companies developing a number of software and hardware tools which featured a host of advanced capabilities like wireframe modeling, freeform surface modeling, solid modeling, validation, verification, simulation, direct output of design data and sophisticated analysis routines. This, in turn, coupled with advances in machinery design and specifications have made it possible to engage in faster machining with increased accuracy and precision.

However, manufacturing is still in a ‘dark age’ with respect to integration and standardization of technologies. The need to have a knowledge-based intelligent system integrating various CAD/CAM/CAE subsystems and process monitoring and control modules, has evoked strong support in the recent past. The absence of a single standard which would have established uniform engineering and technical criteria across the manufacturing community has contributed significantly to the absence of an integrated system. The manufacturing community across the globe has realized the vast potential integrated systems provide in terms of compatibility, interoperability, safety, repeatability, quality to withstand the rising competition and cost effective manufacturing. The call for an improved, vastly superior, “smart” manufacturing system is greater than ever before. In this paper we define the concept of the smart machine supervisory system to monitor and control multiple process modules.

The paper is organized as follows. Section 2 discusses the details and objectives of the Smart Machine Platform Initiative (SMPI). Section 3 describes the survey for various off the shelf commercial products available in the supervisory monitoring and control area. Section 4 includes the definition of the supervisory system with its technical and organizational/business requirements and a prototype application. Section 5 discusses the issues and limitations in realization of the supervisory system and section 6 concludes the paper with discussion and future work.
2. Smart Machine Platform Initiative

The manufacturing base has been a critical component of the US economy. Global competition, better quality, rising labor costs and low cost offshore outsourcing has made a significant detrimental impact. In light of all the issues a Coalition on Manufacturing Technology Infrastructure (CMTI) was formed represented by Association for Manufacturing Technology (AMT), National Center for Defense Manufacturing and Machining (NCDMM), National Center for Manufacturing Sciences (NCMS), National Coalition for Advanced Manufacturing (NACFAM), National Tooling & Machining Association (NTMA), Society of Manufacturing Engineers (SME), and TechSolve to revamp the manufacturing sector. TechSolve in support with AMT and CMTI is currently managing the Smart Machine Platform Initiative (SMPI) funded through Dept. of Defense. SMPI aims to address the long standing issue for increased innovation in manufacturing. SMPI is a reinvention of the basic manufacturing environment, enabling dramatic improvements in the productivity and cost of designing, planning, producing, and delivering high-quality product within short cycle times. TechSolve has established an advisory group represented by academia, industry and government institutions.

Smart machine program at TechSolve consists of six major thrust areas namely Machine Tool Metrology (MTM), On-Machine Probing (OMP), Tool Condition Monitoring (TCM), Health and Maintenance (H&M), Intelligent Machining (IM) and the Supervisory System (SS). A smart machine is defined as a machine that knows its capabilities to come up with the most efficient way to produce a correct part the first time, every time and will check and monitor itself using the data to help close the gap between the designer, manufacturing engineer, and the shop floor. The supervisory system is the manufacturing expert system which works like the brain of a smart machine. It will collect information from individual thrust areas and take a decision based on predefined business and logic. The supervisory system will address the need for an all encompassing system responsible for coordination of manufacturing activities, monitor technologies, construct inputs and initiate outputs to accomplish the “First Part Correct” philosophy.

3. Literature Survey

A comprehensive literature survey was conducted to identify the integral components of the supervisory system and to bring to surface critical issues involved in building such a system.

Current R&D in academia and industry relate to the development of Open Architecture Systems viz. Open, modular architecture control (OMAC) technologies group; OSACA (Open System Architecture for Controls within Automation systems); JOP (Japan FA Open Systems Promotion Group) and STEP-NC [1].

Existing applications have been mostly limited to regulating a single process using a single process variable [2]. It is well established that multiple process monitoring and control improves productivity and reduces machining time [5]. However, it was observed
that within the existing applications themselves, there are no established procedures or standards to implement effective process control [3]. Most of these applications use propriety software and hardware that is bundled together making it incompatible with other applications.

There is also a clear underdevelopment in the sensor fusion technologies as well as systematic design approaches (optimization systems) to intelligently construct and implement multiple process control modules that can be used in the manufacturing industry [4]. Ad-Hoc construction of the various process controllers according to a particular manufacturing system have also not contributed towards the deployment of multiple process control.

A survey was conducted to probe the market for commercial products and technology providers related to supervisory monitoring and control. Products related to Open Architecture Control, Machine Condition Monitoring and Control, Manufacture Monitoring and Management Systems were identified and their capabilities reviewed [1]. Table 1 lists the current commercial products and technology providers related to supervisory control area.

**Table I: Commercial Products and Technology Providers Related to Supervisory Control**

<table>
<thead>
<tr>
<th>Open Architecture Control</th>
<th>Machine Condition Monitoring and Control</th>
<th>Manufacture Monitoring and Management Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDSI Open CNC</td>
<td>Siemens SINUMERIK 840Di</td>
<td>Freedom E-log</td>
</tr>
<tr>
<td>Cimetrix – CIMControl</td>
<td>GE Fanuc</td>
<td>Artifact Machine Monitor</td>
</tr>
<tr>
<td>Cranfield Precision (Unova) -</td>
<td>Okuma</td>
<td>B2D Solution Manufacturing</td>
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<tr>
<td>Cranfield Controller</td>
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<td>Indramat - System 200</td>
<td>Marposs</td>
<td>ARTIS system</td>
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<td>Kistler</td>
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<td>SKF</td>
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<td>Prufttechnik</td>
<td>Pepperl+Fuchs</td>
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<td>National Instruments</td>
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<td>Prometec</td>
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<td>CNC Engineering</td>
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<td>HAAS CNC Auto-Motion</td>
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<td>Microstar</td>
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4. **Supervisory System**

As stated earlier, the smart machine is broadly considered as an amalgamation of six thrust areas namely Machine Tool Metrology (MTM), On-Machine Probing (OMP), Tool Condition Monitoring (TCM), Health and Maintenance (H&M), Intelligent Machining (IM) and the Supervisory System (SS). The supervisory system is in essence the nervous
system of the smart machine. It has the ability to monitor technologies running on the CNC and coordinate their activity by initiating output controls.

We define the supervisory system as a “system that integrates and coordinates individual process monitoring and control systems such that a globally optimal machining solution can be delivered real time for desired quality and maximum productivity”.

Figure 1 shows the smart machine supervisory system definition concept encompassing of all the thrust areas within SMPI.

![Figure 1: Smart Machine Supervisory System](image)

### 4.1 Technical Requirements

The Smart Machine needs a supervisory system which would facilitate seamless communication between other process control and monitoring systems on the machine. Such an integration of the existing and disparate subsystems under a single supervisory system would facilitate the delivery of over-arching functionality of the component subsystems. The constructing of various inputs and subsequent output controls must be done in real time so that the adjustment of multiple process controls would contribute to the success of the first part correct philosophy. Such a functionality delivered in real time would enable the global optimization of the manufacturing process. The system architecture should have following characteristics:

- **Flexible**: Handle changes in product design and fluctuations in product mixes and volumes.
- **Modular**: A modular approach will enable easy plug and play of system components without the need for significant re-engineering
- **Scalable**: Scalable control system can be applied across a broad spectrum of applications
• Open: Allows integration of hardware and software components in the “de facto” standard environment and the ‘plug and play’ functionality.

4.2 Organizational/Business Requirements
Apart from the technical requirements associated with the development of a supervisory system, it should also satisfy certain organizational functions expected of such an aggregation of subsystems. The supervisory system must ensure that the process of interlinking different software systems and computing tools does not throw in interface errors and delay organizational functions. An accurate interface would greatly increase the scope of what can be actively sensed in the manufacturing process and equipment. However, such an enhancement of sensory capabilities would generate lot of redundant data. As such, the supervisory system is developed in such a way that multiple data entry and storage is eliminated. This would, in effect, also reduce the costs associated with such redundant data storage and also reduce the errors contributing to data consistency.

Building up an interface that would link various component subsystems would be done either physically or functionally. The interface could use various techniques to interlink between the interfaces of multiple subsystems. In the event that no direct interface can be developed between various subsystems, the supervisory system needs to provide for the required mappings in between the subsystems. The development of the supervisory system is thus, bound to utilize a number of techniques and technologies like manual programming, business process networking applications as well as other application integrator tools. This would require substantial amounts of investment to accrue the necessary and more importantly, the capable integrator and networking applications to build up the proposed supervisory system.

4.3 Architecture
The architecture of the supervisory system is classified into two hierarchy levels.

i. Communication Level (Awareness)
ii. Decision Level (Responsiveness)

The communication level of the supervisory system is responsible to maintain ‘awareness’ of the functioning of various component subsystems on the smart machine. It is also accountable for ensuring the real time information flow (responses and inputs) among all the subsystems of different thrust areas within the smart machine.

The decision level of the supervisory system will be concerned with the generation of the response based on the current functioning of the machine, previously stored machine data (knowledge base) and pre-programmed effectors (adaptive optimization agent). All the responses pertaining to the adjustment and calibration of machine tool need to be initiated in real time. The decision level of the supervisory system utilizes the available
information in the knowledge base to optimize the given process model with given constraints and objective function. This will address the issue of priority assignment, multiple process control and conflict resolution among subsystems. Figure 2 illustrates detailed schematic of the supervisory system architecture illustrating transfer of control data parameters among various thrust areas of the smart machine.

4.4 Prototype Application

Objective: The objective of developing a prototype application of the supervisory system is to facilitate black box and white box testing and evaluate the functionality before moving towards complete integration of other thrust areas. The prototype supervisory system can serve as the proof of concept.

Technologies Identified: A number of technologies have been identified that would aid in the development of the supervisory system. Notable among them, which are currently being utilized to develop a prototype are:

- I/Gear Data Transport Utility (DTU)
- Kepware KepServerEx
- GE Fanuc FOCAS drivers
I/Gear DTU is a multi-threaded programming interface that has the ability to process transactions between distinct technologies [7]. It provides an open architecture for integrating various manufacturing systems and has the ability to develop custom business logic with easy to use high level programming languages.

Kepware KepServerEx is an OPC compliant communication server which is middleware for communication between CNC (server) and client applications like I/Gear [8].

Fanuc FOCAS (Fanuc Open Factory CNC API Specifications) libraries are a communications driver product that are intended for use with OPC-supported applications to connect them to GE Fanuc CNC models in the ‘i’ series [10].

**Setup and Procedure:** The critical aspect in setting up a prototype supervisory system is to develop a working architecture plan on how the identified technologies can be made interoperable. The architecture consisted of use of an open API communication server, KepServerEx, as a means of communication between I/Gear and the Machine Tool Controller. I/Gear would also interface directly with the individual thrust areas of the smart machine as shown in Fig. 3.

![Principal architecture plan of Supervisory System](image)

**Figure 3: Principal architecture plan of Supervisory System**

The prototype supervisory system communicates with one of the subsystem components, specifically Caron Engineering System, to generate an undercut alarm [28]. The alarm generation would trigger an interruption type custom macro in the Fanuc controller which is preprogrammed to execute a retract program to prevent damage to the tool. An USB controlled digital output generator was also used to aid in the implementation of the interruption type custom macro. LabVIEW (National Instruments) was used to trigger the interruption type custom macro.
An interface between the machine tool (Milltronics HMC-35 running on a Fanuc oi-mc controller) and certain thrust area technology subsystems viz. Blum Laser Systems and Caron Engineering Systems pertaining to TCM. Manual programming was done to bring into effect an interruption type custom macro function built into the Fanuc controller to control machine tool movement upon alarm generation.

![Supervisory System Functional Schematic](image)

Figure 4: Supervisory System Functional Schematic

**Results:** The communication level of the supervisory system was effectively deployed. The retract program (interruption type custom macro call) was successfully activated in case of any alarm being generated by the Caron system to prevent damage to the machine tool.

5. **Issues**

The deployment of the prototype supervisory system has exposed many issues which need to be addressed before the realization of a genuine ‘supervisory system’. The main issues identified were interoperability, absence of standardization and advanced knowledge based adaptive optimization systems.

**Interoperability:** Interoperability in the manufacturing world relates to the exchange of information among hardware(s), software(s) and among both together. Proprietary software and hardware is used which is bundled together making it incompatible with other applications. Most of the hardware systems as well as software systems within the manufacturing world have a copyright over their products.

**Absence of Standards:** The lack of unifying standard in the automation industry is an issue of grave concern for the smart machine program. The lack of a universally embraced standard has posed serious problems during the integration of component subsystems. There is lack of formats for data structures for multiple levels of communication within the smart machine systems.
In addition, there is a lack of standards for representation of features and attributes, and communication between applications. It is difficult to create a direct interface between two technology systems. As such, a large amount of manual programming and existing integrator technologies aim at mapping the functions between subsystems to enable seamless dataflow among them.

MTConnect is an open non-proprietary standard, being developed at the University of California at Berkeley which will complement the smart machine program. It a middleware standard that would provide the capability to pass data, with existing data transfer capabilities and formats, to higher level systems using the XML based standard. Future prototype supervisory systems are being developed in the point of view to support MTConnect standard [9].

![Figure 5: MTConnect Standard [9]](image)

**Knowledge Based Adaptive Optimization Systems:** The optimization system within the supervisory system uses the archived data in its knowledge base to optimize the process model. The optimization system will play a vital role in successful implementation of the supervisory system. Knowledge-based optimization system use analytical as well as heuristic techniques for decision-making. It consists of subsystems namely knowledge base, inference engine, and user, data and knowledge-base interfaces.

### 6. Conclusion and Future Work
The supervisory system is an integral component of the smart machine, responsible for optimizing the machining process for cost effective quality while facilitating the seamless
flow of information between component subsystems of the smart machine. A prototype application of the smart machine supervisory system with emphasis on the communication level (Awareness) of its architecture was developed and demonstrated at TechSolve.

Future work on the supervisory system will be directed towards development of an interface between other thrust areas of the smart machine like supervisory system and health & maintenance. The data collected will be used for data mining and knowledge discovery purposes. Implementation of self-learning and self-correcting techniques will be a major research thrust. Implementation and demonstration of MTConnect protocol on select few systems is planned. The interoperability standards between various application and controllers should be well defined and commercially accepted. Knowledge-based adaptive optimization systems are being actively researched in academia and industry. Integrating a scalable and open knowledge-based system would greatly enhance the successful deployment of a smart machine.

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