SMART MONITORING OF CUTTING TOOL BASED ON PRE-PROCESS DATA

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ABSTRACT
CNC machine tools have contributed in a very large extent, to the rise in highly ingenious manufacturing processes. The rise of the CNC machine tool coupled with the advent of sophisticated monitoring and control systems have ensured the tremendous improvements on the efficiency front over the past few decades. There are a number of technologies available in the market today, which meet the requirements of specific technical area. But the sin qua non of a successful industry lies in its ability to facilitate continuous technology change and development to maintain its edge in the competitive arena.

The Smart Machine Program Initiative (SMPI) at TechSolve, Cincinnati aims at bringing together six distinct thrust areas viz. Machine Tool Metrology (MTM), On-Machine Probing (OMP), Tool Condition Monitoring (TCM), Health and Maintenance (H&M), Intelligent Process Planning (IPP) and Intelligent Machining Network (IMN) under the surveillance of an expert manufacturing system called the Supervisory System (SS), which acts like the brain of the entire manufacturing process.

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. It aims at developing a harmony among individual technologies of the aforementioned thrust areas and ensuring that all of them function together as a single system. Such a Supervisory System would be capable of delivering the overarching functionality of the manufacturing process in a more optimal scenario.

Functionality may also be added into the CNC system because of enhanced data interactions between the component subsystems. As a first step in this direction, TechSolve has initiated an integration module to bring together Tool Condition Monitoring (TCM) Technologies with data from Intelligent Process Planning (IPP) as the inputs.

The paper starts with the detailed overview of the SMPI project, the supervisory system and its importance. It then proceeds to explain how integration was bought about between TCM and IPP modules by using predicted power during the cut as a premise for calibration tool cuts. It also proceeds to explain how the integration added functionality in terms of monitoring tool alarms and adaptive control by using a good tool in place of a bad tool. The paper also proceeds to explain how the incorporation of the health index of tool holder can also enhance the functionality of the integration module. The paper concludes by setting down an agenda for future work and proposing the benefits of the supervisory system to the Smart Machine.

INTRODUCTION
The introduction of Computer Numerical Control (CNC) in the early 1970’s [5] have contributed in a very large extent, to the rise in highly ingenious manufacturing processes. The transformations were so comprehensive across the
manufacturing world which soon witnessed the development of 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 with a number of advanced features. 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. But the *sine qua non* of a successful industry lies in its ability to facilitate continuous technology change and development to maintain its edge in the competitive arena.

However, manufacturing is yet to undergo a radical change 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 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.[6]

**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**

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.

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 for ensuring the real time information flow (responses and inputs) among all the different SMPI modules. On the other hand, the decision module is concerned with the actual responses initiated by the Supervisory system based on inputs from other SMPI modules.

**SMPI TECHNOLOGY REVIEW**

There have also been a number of other technologies that have been identified by other thrust areas. Foremost among them are Caron Engineering CEITMAC Tool and BLUM tools used by Tool Condition Monitoring (TCM), ThirdWave AdvantEdge Production Module by Intelligent Process Planning (IPP), WatchDog Agent by Health and Maintenance (HAM).

CEITMAC Tool by Caron Engineering[1] is a technology used by the Tool Condition Monitoring Module of the Smart Machine to determine and monitor the in-process condition of the tools, including wear, breakage, missing tool, and collision. It is a power sensor based application which monitors the spindle power and analyses it to monitor tool wear and other tool defects.

ThirdWave AdvantEdge Production Module[2] is used by Intelligent Process Planning in its efforts to simulate machining process in order to generate, verify and optimize tool paths based on its own Machining Performance Database and constraints associated therewith, in order to achieve optimum machining processes.

WatchDog Agent[3] was developed by the IMS Center at the University of Cincinnati to aid the efforts of the Health and Maintenance SMPI module, with a goal to achieve a health
monitoring system capable of accurately monitoring and predicting the machine health for near-zero downtime.

The growing number of technologies within the Smart machine program brings out the all important question of how to coerce a seamless communication among the individual technologies and thrust areas. MTConnect was seen as a solution to this conundrum.

MTConnect [4] 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.

It was also proposed to use the Interruption Type Custom Macro [8] to successfully demonstrate the capabilities of the supervisory system. In Fanuc controllers, when a program is being executed by the controller, it is possible another program can be called by inputting an interrupt signal (UINT) from the machine. This function is referred to as an interruption type custom macro function. The format is as follows:

\[ \text{M96 POOOO;} \quad \text{enables the macro interrupt} \]
\[ \text{M97;} \quad \text{disables the macro interrupt.} \]

\[ \begin{array}{c}
\text{M96 P0000;} \\
\text{Interrupt signal (UINT)} \\
\text{N0000;} \\
\text{M97;} \\
\text{Interrupt signal (UINT)} \\
\end{array} \]

When the interrupt signal (UINT, marked by * in Fig. 1) is input after M97 is specified, it is ignored. And the interrupt signal must not be input during execution of the interrupt program.

The interruption type custom macro was used to handle cutting tool abnormality detected by means of Caron Engineering Systems. The retract program was written in such a way that the tool retracts back whenever the supervisory system detects an abnormality through the Caron tool condition monitoring system.

**INTEGRATING SMPI MODULES / TECHNOLOGIES**

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. It is in this context that the decision module of the supervisory system becomes fairly significant in the overall scheme of the program.

The decision level of the supervisory system will be concerned with the generation of the response based on the current functioning of the machine and inputs from other modules as well. 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 from the SMPI technologies described above to optimize the given process model with given constraints and objective function. Additionally, the supervisory system is also expected to address the issue of priority assignment, multiple process control and conflict resolution among subsystems.

![Supervisory System](image)

**Figure 2:** shows the three different SMPI modules being integrated under the Supervisory System

In current practice, any tool condition monitoring job needs to be set up from the system’s console using the human-machine interface. For Caron Engineering TMAC system all this information is stored in a Microsoft Access database file. Additionally, the current principle of TCM is based on learning a good cut to set limits to determine the tool condition. The signals from one or more power sensors are learned for a correct cut with a sharp tool. Subsequently, the in-process signal is compared against the learned signal and manually set wear, breakage, and missing limits.

This has given rise to one rather disadvantageous scenario. For every new machining process or cut that needs to be monitored, the machine needs at least one part and one new tool for the
learning cycle, without which it is not possible to determine the tool condition during subsequent machining cuts. It also throws up the possibility of the tool and machine not being protected against errors or collisions during the learning cycle.

The other major disadvantage of this approach, in addition to the mandatory use of a learning cut, is that the limits for the Tool Condition Monitoring system are usually based on historical data rather than a scientific approach.

The integration of the SMPI Tool Condition Monitoring (TCM) module and the Intelligent Process Planning (IPP) module was aimed at addressing the former disadvantage. The plan was to do away with the learned cut in the Tool Condition Monitoring cycle by using the physics-based representation of the machining process simulated by IPP technologies viz. ThirdWave AdvantEdge Production Module.

However, the first cut would be used as a calibration cut to account for certain filtering methods or techniques that might have been incorporated internally into the Caron TMAC engine. The approach followed in this integration is illustrated below.

To achieve this task, it was proposed to make use of a certain number of databases that will help in storing and accessing information on the fly by the supervisory system in order to make the decisions. The details of the databases are mentioned below.

1. IPP Tooling Database: ‘Intelligent Process Planning’ populates the database of properties of tooling necessary to generate the part.
2. Machine Tool Database: The database of properties of the tooling existent in the machine tool is populated by the operator at this stage of integration.
3. Tool Assembly Health Database: Health and maintenance populates the confidence value (CV) database. The CV value is a measure of the goodness of the health of the tool assembly.

It was also proposed to develop a ‘standard’ NC program which shall conform to a certain set of guidelines so as to have an uniform basis on which the supervisory system will be able to read the NC program in use to determine the appropriateness of the selected tooling.

A flowchart showing the complete integration approach adopted by the supervisory system is given in Annex A.

**PROTOTYPE IMPLEMENTATION**

As an implementation of the Decision level of the supervisory system, an effort was made to integrate the above technologies under the purview of the supervisory system. LabVIEW was
used as the development platform to build the interface between science based predictions of power in the pre-process (derived from Third Wave) and power-sensor based Tool Condition Monitoring technologies (Caron).

Various correlations pertaining to process uncertainty and Tool tolerances, like limits for wear of the tool, were analyzed so that intelligent knowledge-based decisions about the same can be taken by the supervisory system. A feed forward process design about the correlation between these technologies was then developed to simulate the learning curve in consequent process plans.

A number of tests were conducted to determine a correlation between predicted power and measured power. The fitting relation for TCM peak power prediction obtained was

\[ P_p = 1.396P_{TW} + 0.574 \quad (R^2 = 0.988) \]

Where,

- \( P_{TW} \) is the peak power predicted by Third Wave
- \( P_p \) is the predicted peak power

This was generated from tests at different feeds and speeds.

Subsequently, a number of tests were conducted to investigate the uncertainty of prediction associated with the above equation. The results are tabulated and shown below in Annex B.

In an advancement to the above implementation, and in accordance with the original roadmap of the integration approach, the development of supervisory system extended to the incorporation of Machine Tool health monitoring systems (based on a confidence value generated by the HAM WatchDog Agent which is a measure of the overall health of the tool holder assembly) and real-time data about the machine tool from the CNC controller.

The GUI (Graphical User Interface) of the main LabVIEW program (as shown above) was developed to create a flexible and operator friendly application for use on the shop floor. It automated the whole process with the goal of the supervisory system in view.

**CONCLUSION**

The supervisory system was able to achieve its goal of elimination of learning cycle and monitoring the tool from the very first cut. This has been achieved by initiating the first steps for IPP-TCM-SS integration:

- The IPP output is used as input for TCM system
- Science-based TCM job file generation
- Automation under management of supervisory system

Simple adaptive logic has been embedded into the integration procedure thereby utilizing the services of the H&M module of the Smart Machine as well.

This prototype supervisory system was successfully demonstrated to the industry a number of times during the last quarter of 2008.

**FUTURE WORK**

A number of steps have been identified so that the focus on an even more advanced integration setup can be done with respect to the smart machine program. They are:

- Investigate what would be acceptable limits for the first cut and determine the effect that a change in limit percentage will have on the part
- Correlation between power fluctuations and part characteristics (surface finish, dimensions, tolerances, etc.)
- Determine a procedure to select tool wear limits from a historical database or to determine wear limit for a new tool not included in the database
- Investigate what is the uncertainty associated with setting the wear limit
- Determine a method to capture what is determined as good process
- Use this process as a baseline to generate the future TCM job file

**ACKNOWLEDGMENTS**

Research was sponsored by the U.S. Army Benet Laboratories and was accomplished under Cooperative Agreement Number W15QKN-06-2-0100. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of U.S. Army Benet Laboratories or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation heron.
REFERENCES
3. IMS Center’s WatchDog Agent - http://www.imscenter.net/Research/Core_Research
8. CNC iDocs Document Library, GE Fanuc Automation, January 2006
ANNEX A

FLOWCHART SHOWING THE INTEGRATION APPROACH

START

Read ‘Standard’ NC File

Determine tool number

Build properties of required tool

Get properties of actual tool present on ATC

Do a property match

Match Positive

Match Negative

Find New Tool with required tool properties and CV

Tool Found

Match with Critical CV

CV Test Fail

No Tool Found

Notify operator of inappropriate tooling present in ATC

STOP

Suggest New Tool to operator; Modify TCM settings

Read ThirdWave Predictions; Determine Peak Power; Build Job

Run Calibration; Modify Peak Power as per calibration run

Continue TCM Monitoring; Notify and take adaptive action as suitable
ANNEX B

TABLES SHOWING THE UNCERTAINTY ASSOCIATED WITH THE POWER PREDICTION

Table 1: For Cutting regime different than actual cut: Speed = 1100 rpm, Feed per tooth = 0.1 mm/tooth

<table>
<thead>
<tr>
<th></th>
<th>- 2σ</th>
<th>Mean (X bar)</th>
<th>2σ</th>
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</thead>
<tbody>
<tr>
<td>6%</td>
<td>3.61</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>- 3σ</td>
<td>3.61</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>LTL</td>
<td>3.61</td>
<td>12%</td>
<td></td>
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<table>
<thead>
<tr>
<th></th>
<th>- 2σ</th>
<th>Predicted (Pₚ)</th>
<th>2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>11%</td>
<td>3.81</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>- 3σ</td>
<td>3.81</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>LTL</td>
<td>3.81</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: For Cutting regime for the actual cut: Speed = 1100 rpm, Feed per tooth = 0.15 mm/tooth

<table>
<thead>
<tr>
<th></th>
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<th>Mean (X bar)</th>
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</thead>
<tbody>
<tr>
<td>7%</td>
<td>4.77</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>- 3σ</td>
<td>4.77</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>LTL</td>
<td>4.77</td>
<td>13%</td>
<td></td>
</tr>
</tbody>
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<table>
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<tr>
<th></th>
<th>- 2σ</th>
<th>Predicted (Pₚ)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>11%</td>
<td>4.98</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>- 3σ</td>
<td>4.98</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>LTL</td>
<td>4.98</td>
<td>9%</td>
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