Robotic Machining White Paper Project

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Overview:
The objective of this white paper is to provide an overview of the state of robotic machining as it relates to current technology, market trends, and future potential. It is designed to answer several key questions:

1. Is this an application that merits further development and investment by the RIA membership community?
2. Is this an enabling technology that will address "unmet needs" currently experienced by the end-user community?
3. If the answer is yes to these questions, then why is this technology not being promoted by the membership community and adopted by the end-user community?

The findings of this effort will serve as a tool for the RIA to further educate the membership and end-user community about the potential opportunities for robotic machining.
In April 2008, an announcement was posted to the RIA membership community requesting input from any member who is actively working in the robotic machining segment that was interested in sharing insights and experiences for this project. A questionnaire was developed and distributed to each participant to be used as a guide to prepare for a follow-up telephone interview. Participating companies included both component suppliers and systems integrators. It should be noted that this project focused exclusively on targeting participation from product and solution providers and not end-users.
Introduction:
The first order of business for this project was to define "What is robotic machining, and what types of processes does the definition include?" At first it was thought that this would be an easy process. However, it quickly became apparent that it depended on who was asked. While consensus was never obtained, common themes did emerge from the exercise.

- There is a distinct difference between "Robotic Machining" vs. "Robotic Finishing". Robotic machining involves controlling the path of the robot and tool center point (TCP). Robotic machining is more akin to traditional CNC machining applications (tool-path control) such as drilling, milling, routing and cutting. Conversely, robotic finishing involves controlling the force of the end-effector against the surface of a part and involves applications such as brushing, polishing, de-burring, and de-flashing.
- From a control standpoint, robotic machining involves multiple paths, processes involving the control of five or more axis of motion, and the use of a spindle and tool to "remove material" from a part.

A typical robotic machining cell consists of the following components integrated into a complete system:

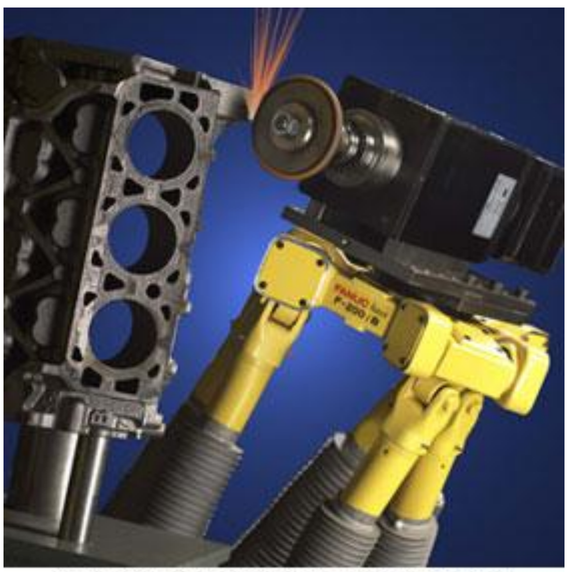
1. Robot (serial or parallel link) and controller
2. Robot compatible CAD/CAM software
3. Spindle and tool
4. Utility Cable Package
5. Application specific ancillary equipment (seventh axis slide, indexing table, force sensor, and vision system)

Market Overview:
To date, robotic machining is being applied in a variety of end-user segments, utilizing several key processes in the manufacture of a broad spectrum of products. The hardness of the material is the determining factor in adoption of this technology and influences where in the manufacturing process this is employed, and the type and complexity of the final product being manufactured. Successful implementation has been demonstrated in a variety of industry segments, from aerospace to motion pictures and from automotive to fashion.
The table below provides an overview of the current end-user specific processes and products manufactured. Some of the unique applications identified that are specific to robot machining include milling molds for the manufacture of hot-tubs and mannequins, rapid prototyping, prototype castings, and cubing of engine blocks.

End-User Segment	Process	Product
All segments	Milling	Rapid prototyping
Aerospace	Grinding, polishing, drilling, cutting	Turbine blades, bulkheads, insulation, wing segments
Automotive	De-flashing, grinding, drilling, milling, cutting	Engines, truck frames, body panels, door knobs, bumpers, stamping dies, sand cores
Fashion	Milling, sanding	Mannequin molds, mannequins

Foundries	De-burring, milling, drilling, routing, finishing	Molds, castings
Marine	Milling	Boat hauls
Medical	Grinding, polishing	Prosthesis
Entertainment Ind.	Milling	Move set props, amusement park scenery
Plastics	Milling, routing	Molds, helmets
Woodworking	Milling, routing	Hot-tub molds, furniture, trim, banisters, modeling board

Overwhelming consensus was reached among participants that robotic machining will not replace CNC machining for 3-4 axis applications, but is appropriate for processes where a CNC machine may be viewed as overqualified (tolerances greater than .0001) Robotic machining is currently viewed as an immediate viable alternative for non-metallic materials and for metals depending on the degree of hardness, required surface finish, and complexity of the final part.



FANUC F-200iB Grinding Engine Block

Motoman DX1350 Routing Plastic

According to Aaron Russick – President of Intelligent Machine Solutions, "Companies that truly understand machining and manufacturing tolerances understand where this technology will be effective and where it will fail. There will always be a place for 'traditional' (CNC Machines...etc.) machines and robotics. We are unique in that we understand both robotic and machine tool industries, build equipment for both industries, and truly understand proper application of both. Our solutions aim to "bridge the gap" where there truly is one between these very different manufacturing methods."

The majority of respondents are not actively marketing "robotic machining," but are actively pursuing "robotic finishing." Robotic finishing is not a new process and has been applied to a variety of manufacturing processes for several years. In fact, many in the industry view this as a mature segment. For most participants, robotic machining products and services constitute less than 5% of existing sales. However, most see this as a growth application segment over the next 3-5 years with the caveat that significant effort is required to educate end-users on the capabilities of robot machining before significant increases in revenue are realized.

KUKA CAD Driven Milling


ABB IRB6660 Robot Milling Aluminum

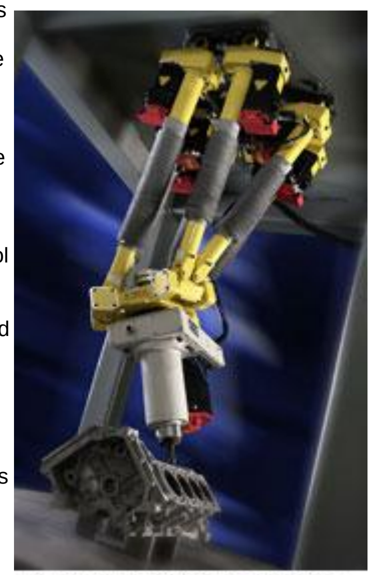
Market Dynamics:
The primary market driver is economic, brought on by increased global competition in the manufacturing industry sector and the need to prevent further movement of the manufacturing industrial base away from North America and Europe to foreign markets with significantly lower labor costs (e.g. Low Cost Country Suppliers). In response, the RIA membership community is focused on providing solutions to end-user manufacturers looking to reduce capital expenditures, increase productivity, and reduce labor costs to remain cost competitive. The net effect from these activities is a trend towards flexible automation and consolidation of multiple processes into a single work cell (part machining, inspection, and finishing).

If the application and material are appropriate, the use of a robot can result in significantly lower capital equipment costs than those associated with a large CNC machine. In all machining applications, both robotic and CNC, the amount of time that the spindle is directly engaged in material removal is a critical metric in determining the profitability of the application. The longer the spindle is engaged in cutting chips, the more profitable the application. In a typical CNC application, the blank is loaded into the fixture, spindle is engaged, blank is machined, spindle is disengaged, finished part is removed, and a new blank is loaded. During the machine load / unload process, the spindle is idle, which decreases the profitability of the part run. A robot for loading and un-loading the machine can be utilized to reduce labor costs. In addition, multiple fixture systems and / or pallet changing systems are available to increase spindle uptime, but all of these add significant costs to an already expensive machine.

An alternative approach to the same process is to integrate two robots into a flexible, multi-stationed, multi-tooled robot machining cell. By employing two robots, one with a spindle / tool for machining and the other with a gripper for load and un-load, in a single work cell that is integrated with a multi-station rotary indexing table as a 7th axis, the end user can achieve a higher throughput at a significant cost savings as compared to the same application performed in a typical 3-5 axis CNC machine center. The spindle up time is dramatically increased due to the robot's ability to move directly from one part to the next. Spindle down-time for load / un-load is eliminated because one robot can remove the finished part and insert a new blank part at the same time the other robot is machining.

The process can be taken a step further, by integrating a robotic tool changing system on to one or both of the robots. This would give both robots the ability to perform primary processes (machining and load / un-load) as well as pick up secondary processes such as deburring, polishing, gauging, and inspection.

The inherent 5+ axis machining capability combined with flexibility, large work envelope, and multiple station capability is a flexible solution that allows end-users to expand the range of machining applications at a price point competitive with a traditional CNC machine. The capital costs for a comparable robotics solution is typically 1/2 – 2/3 of the cost of a CNC machine.


FANUC F-200iB Machining Engine Block

According to Bruce Madden – President - Automation Design Engineering, Inc.
"The economic advantages are predicated upon the ability to use a 6 axis robot with a relative ease of application versus a substantial larger and more expensive 5 axis CNC machine. This advantage is created by the reach and payload capacity of the 6 axis robots with the servo motors being presented in a series."

One example of an emerging application is the finishing of engine block castings. Once the block is removed from the casting process a variety of pre-finish machining processes must occur. After the sand core is removed, the gates and risers are cut and the engine block is cubed. All of these pre-machining processes must take place prior to final finishing by a CNC machine. Current practice is to ship the block from the foundry to a secondary location to perform the various material removal processes referenced above. The logistics of shipping the block to a secondary location result in additional labor and transportation costs. One way to mitigate these costs is to perform the pre-machining material removal processes using a robotic machining work-cell at the foundry. Metal removal at the foundry will reduce the overall weight of the engine block and thereby reduce shipping costs. Furthermore, material removal at the source will reduce the amount of time the block spends in the CNC machining cell, as well as reduce the amount of scrap waste that must be cleaned out of the CNC machine once finishing is complete.
According to Nicholas Hunt - Manager, Product Application, and Sales Support – ABB Robotics – "Robotic machining is an opportunity for Robot OEMs to provide a solution to customers that have not considered robots in their manufacturing process. It also gives customers the opportunity to reduce their capital outlay for a machining center and use a more flexible and less expensive robotic system in many cases. LCC or Low cost Country suppliers. If ever the phrase "necessity is the mother of invention" had pertinence, it's now. Manufacturers are hungry for ways to get higher production at a lower cost.
What's more is that the technology is feature-rich and implemented in a way that makes it viable for small and large companies alike. For example: It could take days, or weeks depending on part complexity, to fine-tune a robot "machining" path. Our Lead-through programming coupled with force control machining software effectively eliminates the two most time-consuming tasks: Path programming with consistent tool orientation; and dealing with the constant changes in material geometry and density.'

Market Barriers to Adoption
The overwhelming barrier to more widespread adoption of robot machining is a general lack of knowledge by the end-user community regarding the capabilities and advantages of robots in machining applications. The CNC end-user community tends to be conservative in nature and exhibit a reluctance to adopt unproven technologies. There is a perception that robots are only taught and programming them like CNC machines is not possible. This perception appears to be a carryover from earlier attempts by the robot industry to apply robotic solutions to an unsuitable manufacturing process . The same perception can be said for robotic machining, which has resulted in an "all or nothing" mind-set by the end-user community. The general perception is that, because robots cannot machine hard materials (steel, titanium etc.) to the same surface finish as a CNC machine, then softer material applications may be automatically excluded in the minds of the end-user.
According to Greg Garmann Development Leader for Software and Controls Technology-f Motoman- "Robotic machining is a growing segment. There is a need to better educate end users on how it can save money, time, and reduce capital equipment expenditures. People in the CNC world are focused on CNC applications. Many don't think outside the box. If we can educate and show them how to reduce capital cost, increase flexibility, they are open to doing new things. Customers are starting to educate themselves and are beginning to come and request robotic machining."

Technical Barriers to Adoption
The approach of this survey was to break-down technical barriers for each system component individually. As indicated above a typical system includes the robot, software, tooling, and ancillary equipment. The table below highlights the technical barriers identified by participants for each system component.

System Component	Technical Barriers
Robot	Accuracy Precision Rigidity Deformation Open vs. closed loop Singularity Granularity of motion Calibration
Software	Ease of use Lack of standards Robot singularity Lack of off the shelf application packages
Tooling	Chattering Vibration Coolant
Ancillary Equipment	Spatial awareness (vision) Fixturing

Based on the information provided by all respondents, it appears that the two underlying technical barriers to widespread adoption of robotic machining are the robustness of the robot arm and the ability to translate simulation and CAD programming into a robot path. The technical challenges associated with rigidity are directly related to the hardness of the materials to be machined. Furthermore, the ability to translate CAD information to robot path is directly related to the complexity and shape of the part to be machined.

According to Virgil Wilson - Material Removal Product Manager – Fanuc Robotics, "With any machining application or solution there is one fundamental requirement that must be taken into consideration. The reactionary forces of any machining process are directly related to the hardness or machinablity of the material being machined. These forces play a large role in determining what robot can be used or whether or not the project is even a viable candidate for Robotic Machining. Without the appropriate rigidity the system will vibrate and chatter affecting tool life, spindle life, surface finish, and cutting tolerances. Medium size to large size serial link robots have enough rigidity to be used in machining applications that are cutting softer material like foam and up to some aluminum applications. Very large serial link robots have enough rigidity for cutting aluminum and some cast iron applications that do not require a high level of tolerance and or surface finish. Parallel link robots can be use with harder materials like steel and for application that require a higher degree of tolerance and or surface finish."

Commercially Available Robotic Machining Products:
According to the information provided, the majority of respondents are actively investing in research and development to overcome the main technical barriers listed above. While both robot rigidity and CAD to robot path were identified, it appears that the robot rigidity issue is still the limiting factor for further adoption.

Robot
It is widely recognized that robot rigidity / stiffness is a limiting factor to wider adoption of robotic machining for harder materials. In order to address this shortcoming, participant robot OEMs have developed robotic arms specifically designed for use in robotic machining applications. All respondents agreed that more rigid and accurate robot arms are required for machining applications of materials further along the hardness scale.
Robot OEMs have pursued two approaches (serial vs. parallel link) to solve the rigidity/stiffness issue. Each approach has trade-offs in terms of stiffness and work envelope area. The serial link approach provides a greater work envelope with greater access to the part, but limited stiffness compared to parallel link. Conversely, parallel link robots provide much greater rigidity, but at a reduced work envelope. The integration of ancillary support items such as a 7th axis linear slide and/or rotary indexing table can increase the functionality and flexibility of the work cell, but at an increased cost.
Below is a list of recently released robot arms specifically designed with robotic machining in mind:

- ABB - IRB 6660 – Serial Link – Recently released robot line dedicated to pre-machining applications in the foundry and casting industries
- FANUC – F200iB – Parallel Link - Engineered for applications requiring extreme rigidity and exceptional repeatability in a compact, powerful package.
- Kuka - KR 500 MT (Machine Tool) – Serial Link - Developed especially for machining to increase machine stiffness. Higher process forces due to modified gear units in the main axes to process up to 8,000N. In addition, the Kuka HA series of robots offer higher accuracy which translates into a better robot path.
- Motoman – DX1350N – Serial Link – Compact and High rigidity robot used for de-burring after casting or machining
- Staubli – RX170HSM (High Speed Machining) - Serial Link – Recently released robot designed specifically for high speed robotic machining applications. Comes with a Fischer-Precise high speed spindle integrated directly into its forearm.

ABB IRB 6600

Motoman DX1350N

KUKA KR 500

FANUC F-200iB

Stäubli RX170HSM

Other robotic technical developments required to overcome existing barriers mentioned by participants include:

- Motion granularity and tighter resolution which is a function of the precision in the gears of the robot arm
- Servo response time or update time
- Easier methods for robot calibration

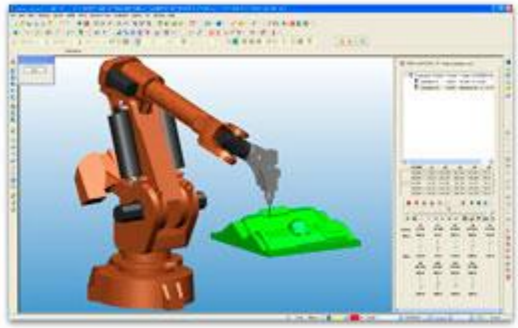
Software

In the past, the primary problem with robots being employed in machining applications has been the lack of industry standards regarding robot OEMs' own proprietary programming language. The CNC industry long ago saw the need for standards and adopted G-codes to control machine motion and M-codes to control machine function. This adoption of machine standards has resulted in a variety of easy to use CAD/CAM programs for CNC machine users. Technical advances in CAD to robot path software over the last few years are viewed as the key enabler to wider adoption of robots for finishing and machining applications. Our findings suggest that software is no longer widely recognized as a barrier to further adoption of robot machining. For example, part complexity is no longer a limiting factor for programming the robot path for finishing and machining applications.

Recent developments have combined CAD / CAM data with virtual simulation and the programming of the robot path. End-users can take CAD information and simulate (dynamic kinematic modeling) the model in virtual space, then translate these results into programming language that provides the correct path of the robot and tool over the part to be machined. By combining CAD, simulation, and robot path into one software package, users can now greatly reduce programming time and costs by decreasing the amount of time required for programming complex shapes from several days to several hours.

According to Chahe Bakmazjian – President - Jabez Technologies Inc.- "In the past, the traditional, multi-software approach of conventional off-line programming solutions forced the use of one software for CAD / CAM programming, another for converting trajectories to robot position and finally a third to simulate and validate the programmed trajectories. Products are now available that seamlessly integrate programming, simulation, and code generation, all inside the Mastercam platform into one software package This allows for the programming of robots from CAD/CAM software as easy as programming a CNC machine."

Listed below are several examples of robot machining related software solutions currently available in the market:



Robotmaster Software Screen Shot

- ABB - RobotWare Machining Force Control (FC) – FC Pressure & FC SpeedChange
- FANUC – ROBOGUIDE, AccuDeflash
- Kuka - kuka.CAMRob – Offers Conversion of CAM data into binary files and KRL programs. Transfers the converted data from an external PC to the robot controller. Provides simulation of the machining process in KUKA.SIM, optimization of the data (point reduction), and machining of shaped parts with the data generated.
- Motoman - G-Code Converter - MotoSim Points Importer - Motoman's MotoSim EG software simulates the robot path generated from the G-code program in the virtual world on a PC, allowing programs to be modeled offline and then downloaded to the robot controller.
- Jabez Technologies – Robotmaster – Converts CNC code from Mastercam based on each parts CAD data, into robot commands.
- KMT- CamPro – PC-based offline programming software that enables manufacturers to seamlessly convert CAM trimming and milling paths into complete 6-axis robot programs.
- Programming Plus – Uses Dellcam Power-Mill software to convert G-code for Kuka Robotics.

Additional needed advances in software mentioned by participants included:

- Standards
- Ease of use
- Execution speed

Tooling

Technical improvements in tooling are not viewed as a critical need by respondents because a wide variety of spindle products are available with the appropriate CNC machining specific tooling. Spindle manufacturers are now providing high-speed motorized spindles specifically designed for robotic machining, with features such as lightweight construction to minimize payload stress on the robot, advanced sealing to minimize threats of contamination, air purge bearing protection, water cooling, and the ability to operate at multiple angles and orientations, ideal for robotic machining. In addition, tooling is available for robotic machining in a variety of standard formats such as HSK, ABS, Grinding Nose, and ISO/CAT.

According to Chad Henry - Applications Engineer at Staubli Robotics USA - "The key distinction between what Staubli offers versus the competition is the integrated high-speed spindle as opposed to an after-market spindle added to a standard six-axis arm. This differentiation allows the integrity of our arm to remain intact while offering a homogenous solution which is dedicated to machining activities."

ABB Robot with Force Control Function Package

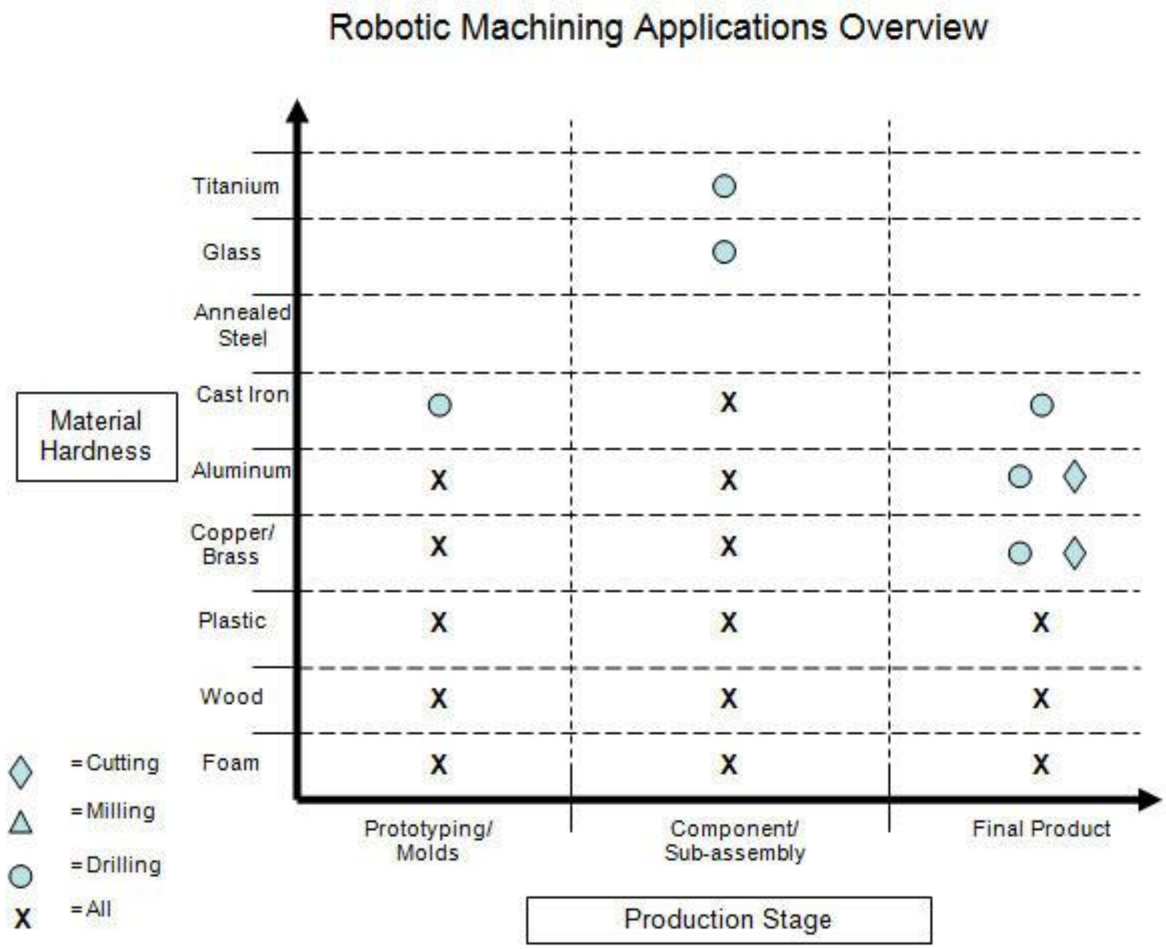
Dynomax HSE Robot Spindle

RX 170 HSM w/ Fischer - Precise Spindle

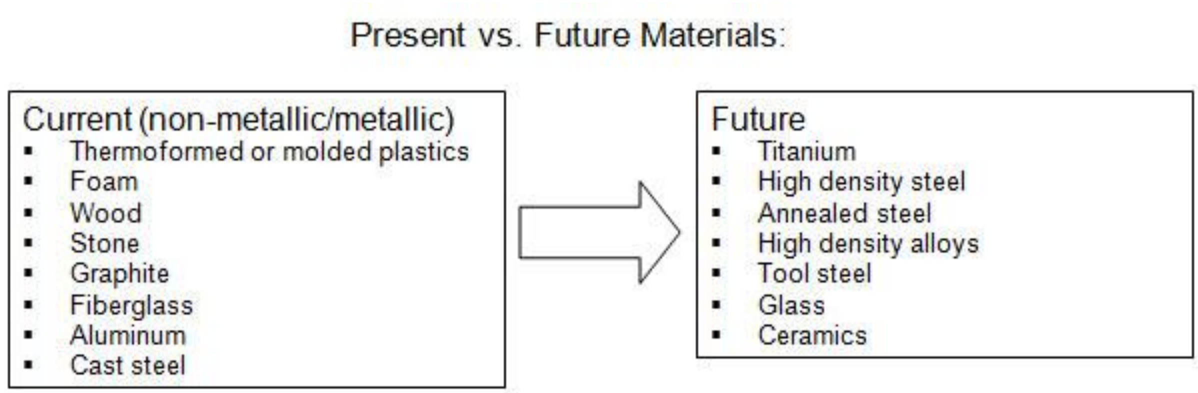
One issue raised was the use of dry tooling vs. wet tooling and how to best incorporate the use of cutting fluids in robotic machining applications on harder materials. A minority of participants expressed a need to incorporate more process specific intelligence into tooling in order to provide real-time feedback (e.g. tool wear, torque feedback).

- Focus on roboticization
- Cooling (ability to machine harder materials)

Future Applications:
Material hardness is a key determinate of where in the manufacturing process robotic machining is currently being applied. As the figure below illustrates, with softer materials robotic machining is being utilized for finished products. However, as one moves further up the hardness scale, robotic machining is limited to prototyping, component and sub-assembly processes.



Present vs. Future Materials:
One area where respondents felt that robotic machining can have an immediate impact on the manufacture of parts made from harder materials is pre-machining. With pre-machining, robots can be used to perform various processes at lower tolerances. This process will allow robotic machining to evolve from the non-metallic and softer metal materials to harder materials in the future.



When asked the question, “From your company's perspective, does robotic machining represent a new phase of innovation in robotic related technologies?”, all respondents, to some degree, answered yes. Below is the one answer that best conveys the overall feeling of all respondents:

"Not so much the application itself, we've been performing machining operations with robots for many years; but the application of the application has evolved tremendously. The term "machining" as it pertains to robotic applications has moved much closer to what the CNC machine tool industry would consider "machining" for all the reasons we've just discussed. We're still not at the performance level of the classic X-Y-Z machining center, and may never get there, but robotic machining is now being taken seriously – and that's a big step. So in that respect – the answer is yes."

Recommendations:

- The RIA has a significant opportunity to assume the lead in educating various end-user segments about the advantages of robotic "finishing" and "machining" technologies. This market application can be expanded through various printed media and conference forums. The net effect of these activities will result in increased sales of products and services by the membership community.
- The key to developing a better understanding of this application segment and its opportunities requires a shift in focus away from how robots can replace CNC machines to the question of how robots can compliment CNC machines. This recommendation is based on the key finding that robotic machining will not replace CNC machining for most 3-4 axis applications.
- Robotic finishing applications, while mature, represent a significant near-term "low hanging fruit" opportunity for the RIA membership to continue to pursue. Furthermore, this will serve as a base to further educate the end-user community for adoption of robotic machining for a variety of applications and end-user segments.
- Possible Actions:
    - A Robotic Machining specific Users Group or Blog should be created to bring the suppliers and end-users together to share common experiences, problems, and potential solutions
    - A Robot Machining Specific DVD with input provided by contributing source companies should be developed.
    - A follow up paper looking at the Robotic Machining from the End User perspective as well as a paper highlighting the technical needs, requirements, and possible standards+

Contributing Sources:
ABB Robotics - Nicholas J. Hunt & Doug D. Niebruegge
AMT, Inc. – Joseph Campbell
Automation Design & Engineering - Bruce Madden & Charles Heisig
Dynomax - Walter Zic
FANUC Robotics - Virgil Wilson
Jabez Technology - Chahe Bakmazjian & Tyler Robertson
Intelligent Machine Solutions - Aaron Russick
KMT Robotic Solutions – Roberta Zald
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