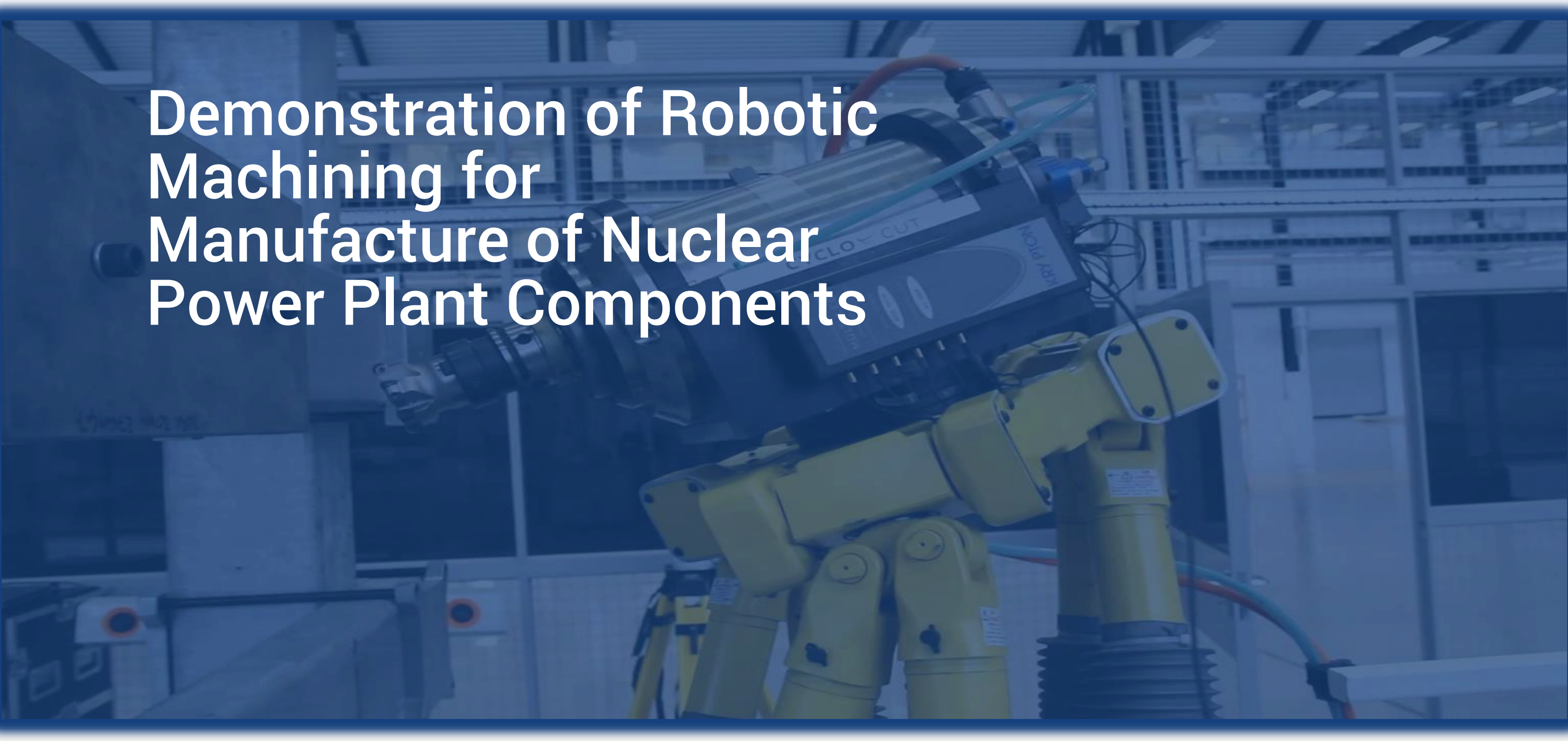
March 2016



Demonstration of Robotic Machining for Manufacture of Nuclear Power Plant Components

Development of the Robotic Machining System

Manufacturing of large scale components in nuclear energy involves of moving the parts between manufacturing facilities and fixturing them to machine tools. Challenges are faced in the manufacture and maintenance of power plant components such as pressure vessels, steam generators and pressurisers due to their size and weight, where moving such components constitutes around 20% of the total cost. Moreover, the capital expenditure and operational cost requirements of conventional machine tools are around $3-5M and $100K per annum, respectively.

The Nuclear AMRC Machining Group, under New Nuclear Manufacturing (NNUMAN) Programme granted by the EPSRC, The University of Manchester and The University of Sheffield, investigated and demonstrated robotic machining as an alternative approach to decrease such costs by employing the "process-to-part" concept. This also offers the benefits of increased flexibility and improve lead-time in comparison to machine tools.

The implementation of the developed methodology in the manufacture of nuclear power plant components is typically expected to:

- reduce the total fixed operation costs by 70%;
- reduce the total variable operation costs by 40%;
- decrease the payback period by 60%.

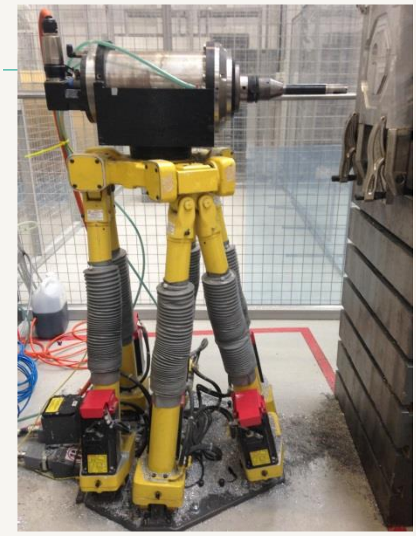
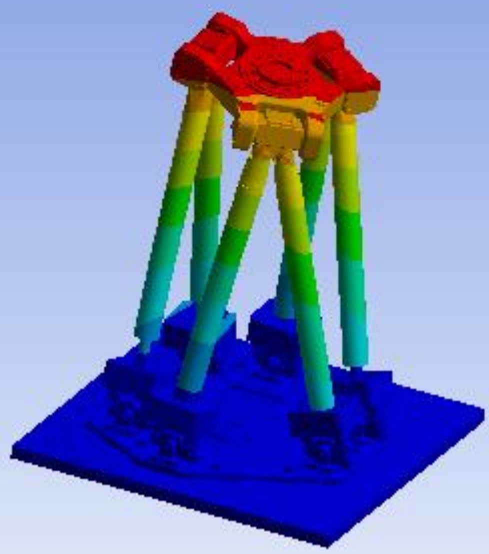


Figure 1: Robotic machining setup at the Nuclear AMRC



There are several challenges associated with robotic machining due to the structural build up, control systems and load carrying capacity of the industrial robots. The innovative part of this project is the way how these challenges are considered concurrently to achieve a common goal considering typical machining operations.

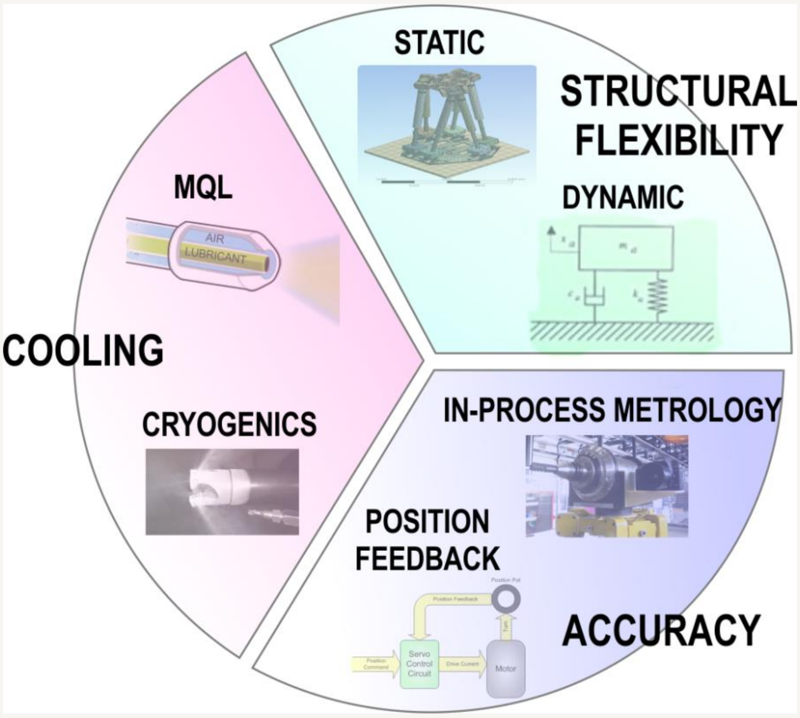


Figure 2: Challenges in Robotic Machining

Overview of Challenges

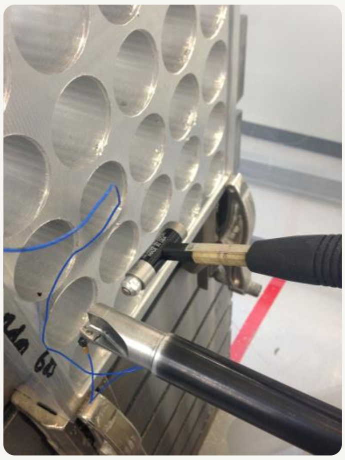
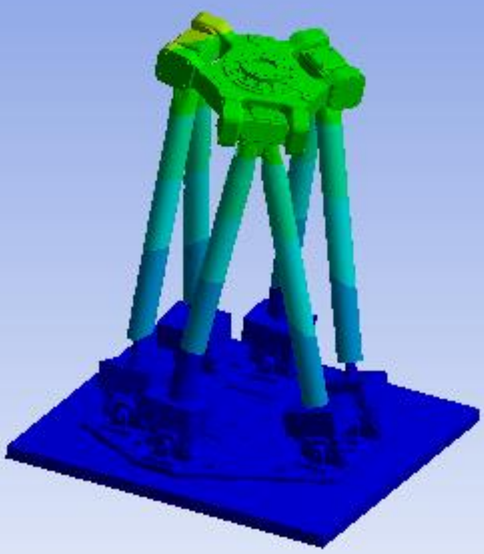


Figure 3: Measurement of tool tip dynamics for modal analysis.



The key capabilities of the experimental, modelling and simulation techniques can be summarized as:

- The flexibility introduced by the industrial robot and its effects on milling dynamics and stability can be quantified.
- The asymmetrical behaviour of the tool tip dynamics due to the introduction of the robot's flexible modes can be identified. The effect if feed rate direction on stability limits can be simulated.
- The tooling geometry, where the position dependency may be minimized can be identified through analytical simulation of tool tip dynamics.
- The actual machining time of the robot can be estimated.
- Selection of milling strategies for increased chatter free material removal in robotic milling can be performed considering robot's control response and tool life under minimal quantity lubrication (MQL).
- The experimentally obtained tool life data can be used in selection of the appropriate MQL conditions and MQL oils.
- Effect of MQL conditions on surface residual stress in milling of nuclear grade steels (AISI316L, AISI304L, SA508) are experimentally quantified.

Key Capabilities

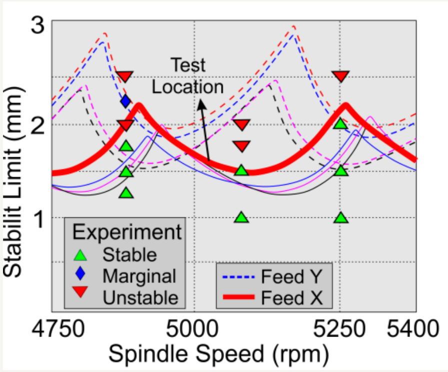
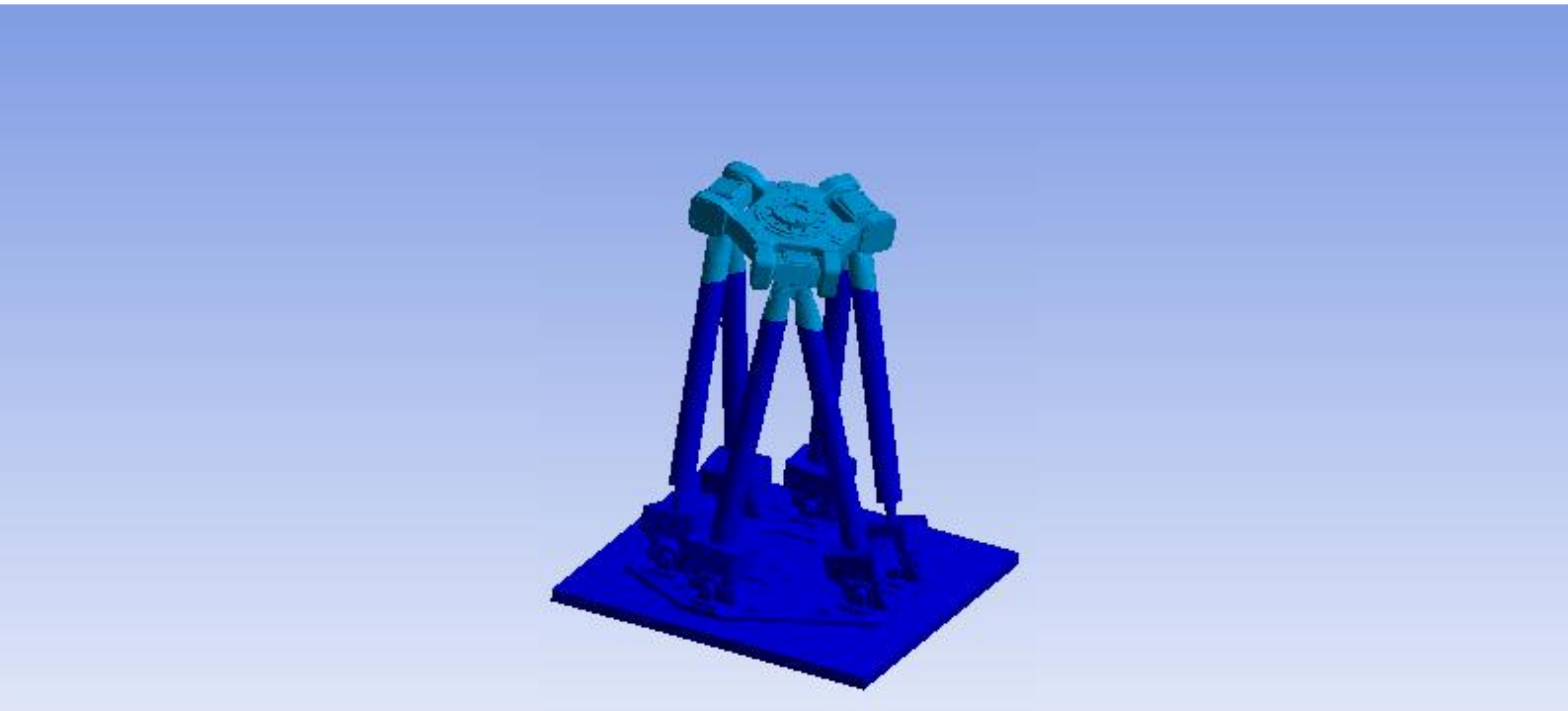


Figure 4: Position and feed rate dependent stability lobes in robotic milling.



The following modelling and simulation approaches are used in a comprehensive manner to demonstrate the capabilities of the developed robotic milling system:

- Receptance coupling for prediction of tool tip FRF.
- Frequency domain simulation of milling stability.
- Finite elements method (FEM) to predict structural modes of the robot and their variation with the robot pose.
- Simulation of robot kinematic motion and control response.

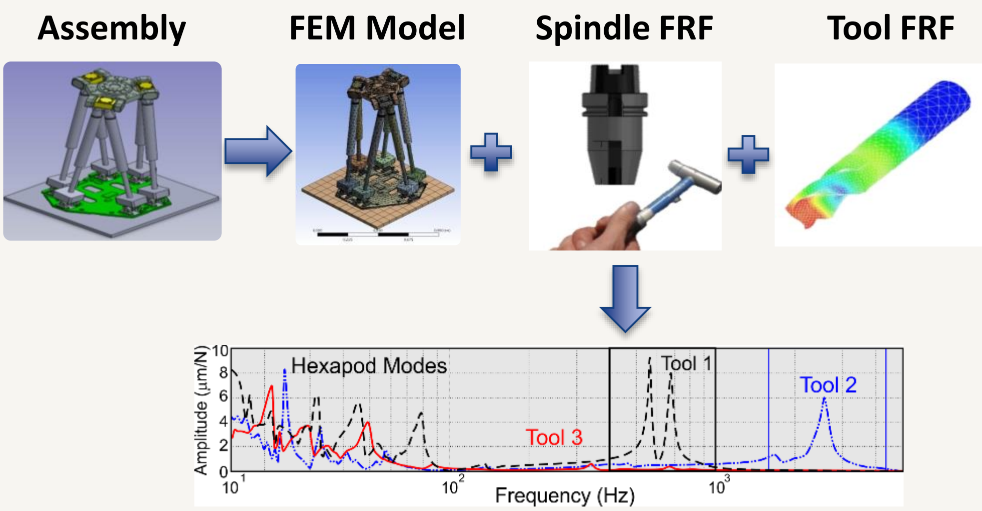


Figure 5: Prediction of tool tip dynamics in robotic milling

Modelling Approaches

- **Frequency domain stability analysis**
- **Receptance coupling**
- **FEM**
- **Control response modelling**

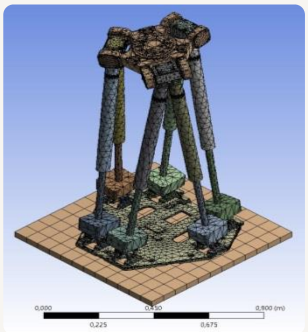
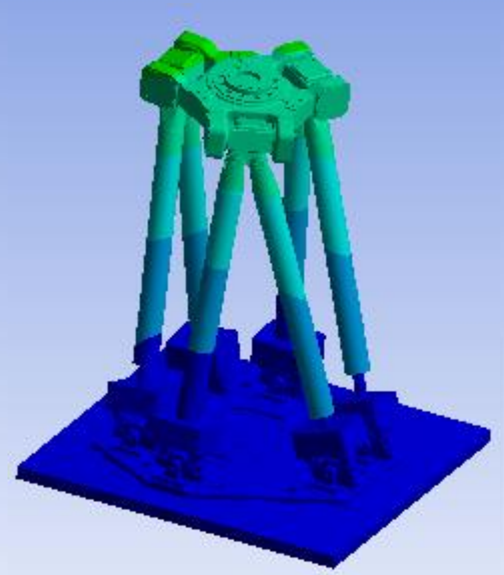


Figure 6: FEM model of the hexapod robotic milling unit assembly



Development of Robotic Milling Strategies for Machining of Nuclear Grade Steels

The Nuclear AMRC, with the support of the University of Sheffield and the University of Manchester, successfully developed a unified modelling and simulation scheme in order to simulate the dynamics of robotic milling together with control response of the robot carrying out the milling task. The developed scheme is able to demonstrate the favorable tooling conditions and milling strategies for increased chatter-free material removal, obeying the motion limits of the robot and tool life constraint.

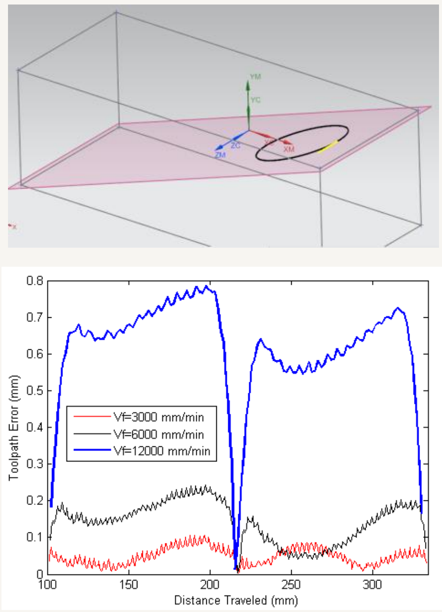


Figure 7: *Tool path contouring error in robotic milling of circular features (at various linear feed velocities)*

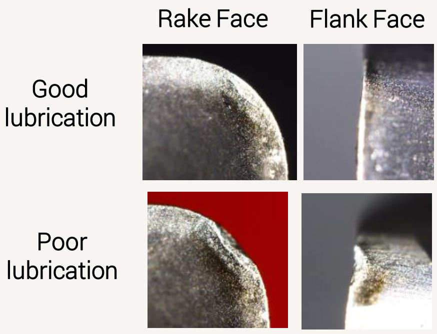
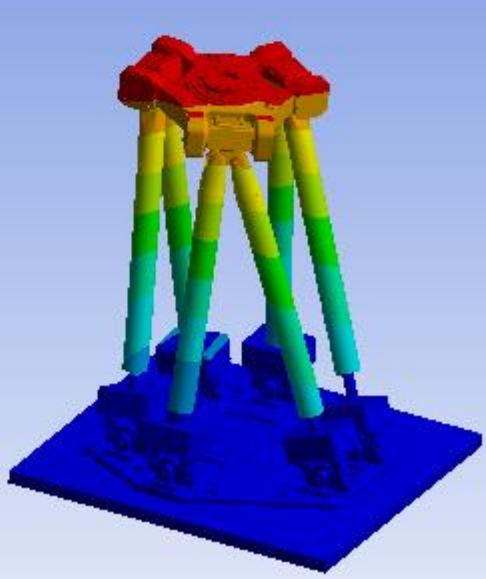


Figure 8: *Effect of MQL conditions on tool wear after 20 minutes milling of AISI316L*



The Nuclear AMRC have developed comprehensive experimental techniques and simulation approaches those have been applied to identify and address the key challenges in robotic milling of nuclear power plant components. Integration of metrology techniques is required to improve position feed back and tool path contouring accuracy. Tooling conditions should be selected considering the low frequency modes introduced by the robot.

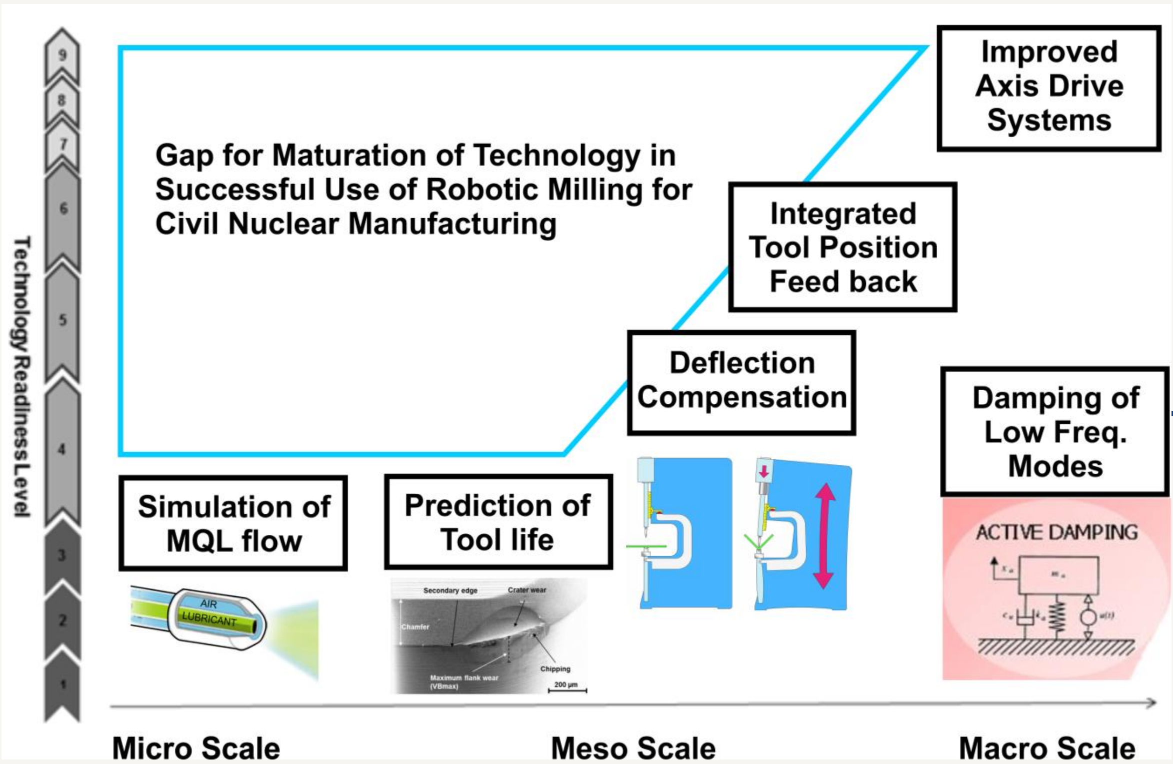


Figure 9: *Technology roadmap for the maturity in modelling and simulation of robotic milling technology- 2016*