

REVIEW PAPER

Active fixturing: literature review and future research directions

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Fixtures are used to fixate, position and support workpieces and represent a crucial tool in manufacturing. Their performance determines the result of the whole manufacturing process of a product. There is a vast amount of research done on automatic fixture layout synthesis and optimisation and fixture design verification. Most of this work considers fixture mechanics to be static and the fixture elements to be passive. However, a new generation of fixtures has emerged that has actuated fixture elements for active control of the part-fixture system during manufacturing operations to increase the end product quality. This paper analyses the latest studies in the field of active fixture design and its relationship with flexible and reconfigurable fixturing systems. First, a brief introduction is given on the importance of research of fixturing systems. Secondly, the basics of workholding and fixture design are visited. After which the

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state-of-the art in active fixturing and related concepts is presented. Fourthly, part-fixture-dynamics and design strategies which take these into account are discussed. Fifthly, the control strategies used in active fixturing systems are examined. Finally, some final conclusions and prospective future research directions are presented.

Keywords: Active fixturing; Reconfigurable fixturing technology; Part-fixture dynamics; Control design; Active fixture design; Fixture verification analysis

1. Introduction

Workholding devices and systems, such as fixtures, are of paramount importance within a manufacturing environment. They exist in virtually any manufacturing context, instantiated in geometries and layouts that span from a simple vice to a complicated robotic cell. Fixtures form an important group within the workholding systems family and are mostly used when precise and repeatable locating of the processed workpiece is required.

Fixtures can affect the performance of a manufacturing line in a number of ways. Firstly, the flexibility of the line is largely dictated by the selected fixturing solution. A fixturing system that demands significant effort to be adjusted to accept a new product geometry, can annul the benefits of modern numerically-controlled (NC) machine-tools and automated manufacturing cells. On the other hand, fixtures, due to their immediate contact with the workpiece largely determine the outcome of the manufacturing process. Geometrical variations in the features of the fixture reduce the locating accuracy of the workpiece relative to the global coordinate frame of the manufacturing process. This can result in the production of out-of-tolerance parts. Furthermore, fixtures affect the static and dynamic rigidity of the workpiece. A poorly designed fixture may result in over-clamping and excessive vibration. These, in turn, lead to dimensional inaccuracies, reduced surface quality and even separation between the fixture and the workpiece, causing the part to be released, ultimately damaging the processing station, halting the production and even injuring personnel sometimes.

The previous clearly highlights the importance of fixtures. This is why intensive re-

search efforts have been dedicated to the field of fixtures, especially over the last few decades, to achieve cost reduction by means of automation and flexibilisation of the production. This work has appeared in review papers and standard textbooks and is generally focussed on:

- (1) computer-aided fixture design, which also includes automatic design (issues) and fixture layout optimisation, as covered by Bi and Zhang (2001), Boyle *et al.* (2011), Cecil (2001), Hargrove and Kusiak (1994), Kang and Peng (2009), Nee *et al.* (1995, 2004), Rong *et al.* (2005), Shirinzadeh (1996), Trappey and Liu (1990) and Wang *et al.* (2010);
- (2) hardware concepts for (automatically) reconfigurable fixtures, treated in the following publications: Bi and Zhang (2001), Dashchenko (2006), Hazen and Wright (1990), Nee *et al.* (1995), Shirinzadeh (1995) and Shirinzadeh (1996);
- (3) fixture design verification, discussions on the latter can be found in the paper by Bi and Zhang (2001) and the textbooks by Nee *et al.* (1995, 2004) and Rong *et al.* (2005).

Recently, a novel form of fixturing has emerged. This fixturing technology is based on sensor-based fixture design concept combined with actuated clamping elements that control the clamping forces in order to minimise part deformation during the manufacturing process. Perhaps the review paper by Leopold and Hong (2009) comes closest to active fixturing, however in that review, there is a strong emphasis on the discussion of the modelling and optimisation of clamping for intelligent fixturing. The present article intends to provide a comprehensive review of the recent and relevant work in active fixturing. Therefore, developments relevant to active fixturing systems in the following areas, which are only marginally and dispersedly touched upon in the other review papers and standard textbooks, are discussed: fixture design concepts, the effect of the dynamic nature of the manufacturing forces on the part-fixture system, especially regarding active fixtures, and active fixture control strategies. Furthermore, the paper aims to identify future developments in the field. It should be remarked here, that the application of the majority of the research carried out in the field of active fixturing and its closely related areas, which are the area of interest of this paper, are machining fixtures. The notable ex-

ceptions where other applications are explicitly mentioned are: Arzanpour *et al.* (2006), Bakker *et al.* (2011a), Izquierdo *et al.* (2009), Jayaweera *et al.* (2011), Kong and Ceglarek (2006), Kurz *et al.* (1994), Martin *et al.* (2011), Papastathis *et al.* (2010), Park and Mills (2005), Wagner *et al.* (1995) and Yamaguchi *et al.* (2010): assembly; Li *et al.* (2010): sheet welding assembly; (Zhang *et al.* 2009a): welding; and Lee *et al.* (1999) and Sah and Gao (2008): stamping.

The paper commences by giving a brief overview of the basic theory behind fixtures and fixturing practices in Section 2. Then, in Section 3, mechatronic applications in fixturing, active fixture concepts and related work are reviewed. In Section 4, modelling methods, which have been applied to capture the dynamics behind the fixture-workpiece systems, and have been implemented to facilitate and augment the fixture-design process, are reviewed. Section 5 looks into the control strategies that have been proposed for fixtures with adaptive characteristics, often referred to as active fixtures. Finally, conclusions are drawn from the literature survey and future trends in fixture research are outlined and explained in Section 6.

2. Fixturing Principles

This section outlines the fundamentals of fixturing. This section is written with those in mind, who have a background in different engineering disciplines, but have a general interest in fixturing. The appreciation of the fixturing principles leads to an understanding of the current developments regarding the emerging active fixturing technology, as the main driving forces behind the development of novel fixturing technologies are the demands for increasing performance and flexibility.

A fixture is a device designed to repeatedly and accurately locate a workpiece in a position and orientation, relative to another workpiece or the reference frame of a machine tool or measurement machine. This process is often referred to as locating. Secondly, fixtures must be able to securely hold the workpiece in the desired location throughout the duration of a manufacturing process without damaging the product. Thirdly, a fixture has to provide ample support of the workpiece during the manufacturing process in order to minimise the deflection due to clamping and machining forces. Furthermore, the fixture

has to be designed such that the workpiece is accessible and requires a minimum level of maintenance during its lifetime.

Fixtures can be used in assembly, machining, measurement and welding operations. They belong to the greater family of work-holding devices. They can be identified and differentiated from other workholding family members through their comprising elements and their functionalities. More detailed information can be found in Hargrove and Kusiak (1994) and Nee *et al.* (1995). Although simple in concept and role, the design of a fixture requires extensive experience and expertise but also imagination and intuition. For this reason, some engineers might state that the design of a fixture is a combination of engineering science and art. Nevertheless, there are some generic guidelines and principles (Nee *et al.* 1995) that the designer can use as the springboard for their work. In general, a fixture comprises three fundamental elements:

Locators: Statically positioned elements with no actuation ability, used to locate the workpiece in a desired position and orientation. A typical fixture has at least 6 locators.

Clamps: Statically positioned elements with actuation ability, used to exert the forces that securely hold the workpiece in its position. A typical fixture has at least 2 clamps.

Supports: Statically positioned elements with no actuation ability, used to locally reduce the elastic deformations experienced by the workpiece due to the loads applied by the manufacturing process. They can also improve the stability of the fixture-workpiece system. There is no limitation to the number of supporting elements used in fixtures. Contrary to clamps and locators, the existence of supports is not compulsory.

Generally speaking, the fixture design process can be divided into four phases: setup planning, fixture planning, fixture configuration design and fixture design verification (Nee *et al.* 1995, Rong *et al.* 2005).

The optimisation of the fixture layout has attracted much research attention. The reason is that for an optimal placement of the locators, the reaction forces are minimised, and as a result the local part deformation is minimised. Furthermore, the fixture can be optimised to minimise the effect of locating errors (Chaipradabgiat *et al.* 2009, Tian *et al.* 2009, Vishnupriyan *et al.* 2011). Or, the fixture layout can be designed such that the part orientation in the fixture is fool-proof. The fixture layout optimisation and evaluation process has been extensively analysed in Wang (2004). Other methods are used

to optimise the fixture layout such as genetic algorithms (Padmanaban and Prabhakaran 2008, Siva Kumar and Paulraj 2011a,b, Yeung 2010). More information on fixture design optimisation and computer-aided fixture design in general can be found in the following review papers and textbooks: Bi and Zhang (2001), Boyle *et al.* (2011), Cecil (2001), Hargrove and Kusiak (1994), Kang and Peng (2009), Nee *et al.* (1995, 2004), Rong *et al.* (2005), Trappey and Liu (1990) and Wang *et al.* (2010).

Fixture design verification or evaluation is traditionally the stage at which the fixture performance is analysed (Leopold and Hong 2009, Nee *et al.* 1995, Rong *et al.* 2005). The fixture performance is of course determined by the resulting end product quality, after all the manufacturing processes planned for that specific part-fixture setup are carried out.

The verification of the fixture design is an important step in the design cycle; Rong *et al.* (2005) and Nee *et al.* (1995) devote the second half of their books on this issue. Leopold and Hong (2009) stress its importance quite early in the introduction of their review paper. Fixture design verification usually consists of a tolerance sensitivity, an accessibility and stability and deformation analysis. This can be done a posteriori. For example Li (2008) made a virtual reality model of a part-fixture system to perform an accessibility analysis. However, the increase in computational power of desktop PCs and the availability and integration of computer automated fixture design tools allows the designer to verify the design already during the fixture layout synthesis. Moreover, the model-based control designs, reviewed in Section 5 rely of course on the mechanical model of the part-fixture system established during the verification.

The previous constitutes a brief introduction to the fundamental of fixturing. Of course, each workpiece, each manufacturing process and each manufacturing environment have their own unique fixturing requirements. This explains the immense research and development efforts that have gone into developing new fixturing concepts and technologies. The most prominent fixturing strategies are generally categorised as follows: dedicated fixtures, modular fixtures, flexible pallet systems, sensor-based fixture design, phase-change based concepts, base plate concepts, pin-type array fixtures, automatically reconfigurable fixtures (Kleinwinkel *et al.* 2006, Nee *et al.* 1995, Shirinzadeh 1995). As mentioned before a poor fixture design can result in excessive clamping forces, strong vibrations, or worse,

unstable workholding. For this reason it is important to optimise both fixture design and clamping forces. More recently, a new fixturing paradigm emerged, called active fixturing. These fixturing systems can adapt the clamping forces online. Of the former strategies, sensor-based fixture design and automatically reconfigurable fixtures (bar the modular fixtures build by robotic systems) are closely related to the newly emerged active fixturing paradigm. For this reason these concepts are discussed together with the active fixturing concept in the following section.

3. Sensing and Actuated Fixturing Concepts

3.1. *Sensor-Based Fixture Design*

Sensor-based fixture design is a fixturing strategy where vision and sensor systems are utilised to ensure that the part is located correctly in the fixture (foolproofing). This is an important step towards the automatic loading into fixtures (Benhabib *et al.* 1991, Rong *et al.* 2005) and also the design of a generation of adaptive fixtures. They do not strictly constitute a separate category of fixture concepts as they take the form of any of the previously mentioned fixtures. The difference is that they bear sensing elements integrated into their structure. In the vast majority of cases, these elements are used to record clamping, reaction and external forces for the purpose of machining condition monitoring. However, position sensors have also been used to record workpiece displacement from its desired location.

The first attempt to integrate sensing capabilities into a work-holding device was made by Gupta *et al.* (1988). This work describes the fabrication of a simple vice comprising two V-blocks, one fixed and one movable. A piezoelectric dynamometer was placed on the fixed V-block to measure clamping forces. Another dynamometer, measuring thrust forces and torque from the drilling tool, was placed below the base of the two V-blocks. The recorded data was used to identify the safe and unsafe clamping force regions in relation to spindle speed and feed rate.

Hameed *et al.* (2004) investigated the performance of a fixture with uniaxial-force-sensor-integrated elements for accurate monitoring of the cutting forces from milling operations. The goal was to alleviate the need for a multi-axis dynamometers.

de Meter and Hockenberger (1997) instrumented a fixture with eddy current displacement sensors to record workpiece displacement from its desired position due to the clamping process. This information was used to compensate the tool path of a milling cutter.

Denkena *et al.* (2009) designed and built a fixture with integrated MEMS temperature and acceleration sensors and strain gauges-based displacement transducers. The sensors and strain gauges have been optimally placed in the design by means of model-based optimisation.

Sah and Gao (2008) made a fixture-die-binder system that can measure the contact forces that can be used to produce a real-time estimate of the contact pressure during the stamping operation for the purpose of process monitoring.

Shirinzadeh (1995) proposed the application of sensors and vision systems to establish the location and orientation of a part and to use this information to control the tooling operations in an assembly fixture, as e.g. used in aerospace industry. Currently this tooling concept is being developed at Linköping University under the name of Affordable Reconfigurable Tooling (ART) (Jonsson and Ossbahr 2010, Jonsson *et al.* 2008).

3.2. *Automatically Reconfigurable Fixtures*

In this section fixtures with automatically self-reconfigurable capabilities are discussed. To the best of the authors' knowledge, the first NC fixtures were conceptualised and presented by Tuffentsammer (1981). In this work two NC fixturing principles were presented: the double revolver and the translational movement. The first one can achieve differentiation in the fixture element position by using independently actuated revolvers, called the primary and the secondary. The primary revolvers take the form of disks, on which a variable number of secondary revolvers is assembled. Each revolver is able to rotate independently. The secondary revolvers bear cylindrical-pin formations, which are positioned eccentrically to the revolvers axis of rotation and are able to extend and retract. By combining the movement of the primary and the secondary revolvers, different fixture set-ups are achieved for a variety of processes. Hydraulic linear actuators, which are positioned above the workpiece, are used to apply the required clamping forces.

The translational-movement-based system uses linear motion to achieve the necessary readjustment of the position of the elements. Just as in the double-revolver concept, this

fixture deploys cylindrical-pin formation that can extend and retract to conform to the workpiece geometry. Contrary to the previous concept, however, the clamping elements of this NC fixture are situated at the side of the workpiece and are positioned on slides with vertical orientation.

The two previously mentioned principles are presented schematically in Figure 1. These principles have also been used by Du and Lin (1998) and Du *et al.* (1999) in their proposals of NC fixturing concepts. A short discussion on the working of the concept is given in Section 3.3.

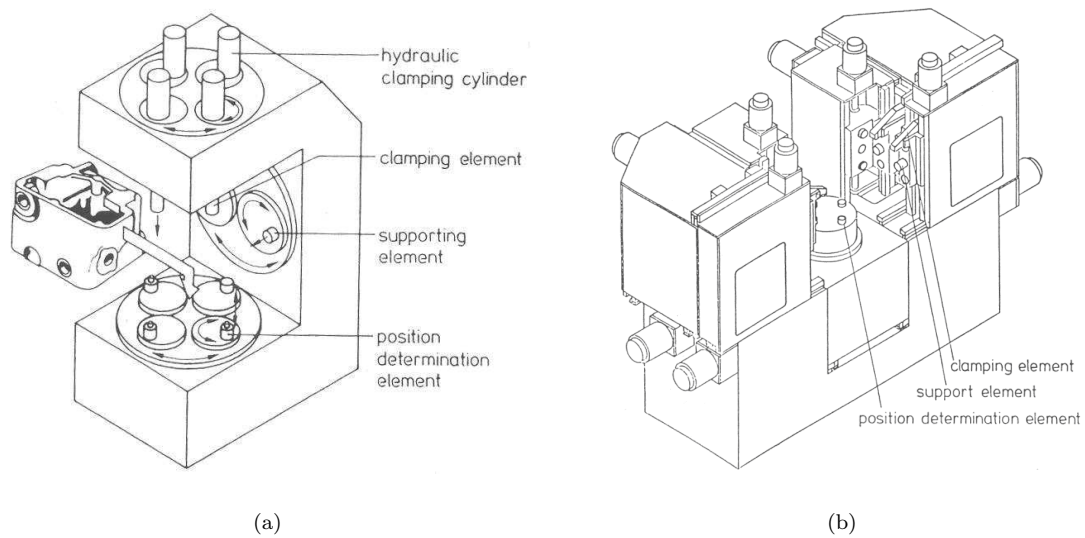


Figure 1. Two NC fixturing concept utilising the (a) double revolver and (b) translational movement principles (Tuffentsammer 1981, Picture 23 and 24).

When making a taxonomy of the fixturing techniques, the first of these concepts are the actuated pin-type array fixtures as described above. Secondly, concepts based on grippers that grasp objects are discussed by Nee *et al.* (1995). Often these designs are used in micro-machining and are also known as “micro-manipulator” or “tweezers”. The positional accuracy and load bearing capacity of dexterous grippers for larger object is generally lower than that of fixtures. For this reason, other gripping strategies have been proposed, e.g. the designs presented by Sudsang *et al.* (2000) and Chan and Lin (1996) where a part can be grasped, positioned and orientated. Both concepts are respectively shown in Figures 2 and 3.

The remaining two main fixturing concepts are robots in the form of parallel kinematic

mechanisms (PKMs) and Cartesian coordinate robots. Currently, PKMs are mainly applied in assembly fixtures (Kong and Ceglarek 2006). See e.g. Kurz *et al.* (1994), Arzanpour *et al.* (2006), and Wagner *et al.* (1995), for early applications of PKMs in fixturing, while more recent approaches can be found in papers by Bi *et al.* (2008), Dashchenko (2006), Jonsson and Ossbahr (2010) and Li *et al.* (2010). Molfino *et al.* (2009) propose the use of many PKMs (a swarm) to be able to relocate support points during the machining process. An illustration of this concept is shown in Figure 4(a), where a group of PKM-based fixture elements provides extra support at the tool location. PKMs can be

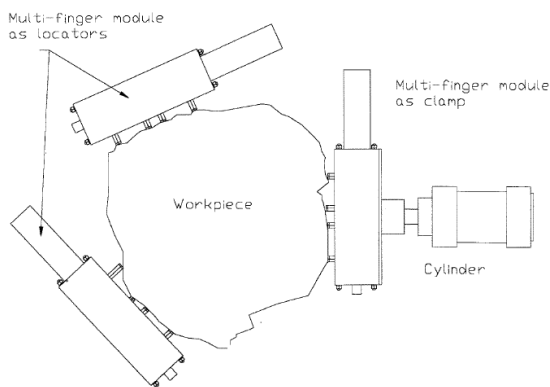


Figure 2. Setup for the multifinger modules as a CNC controlled modular fixture developed by Chan and Lin (1996, Fig. 11).

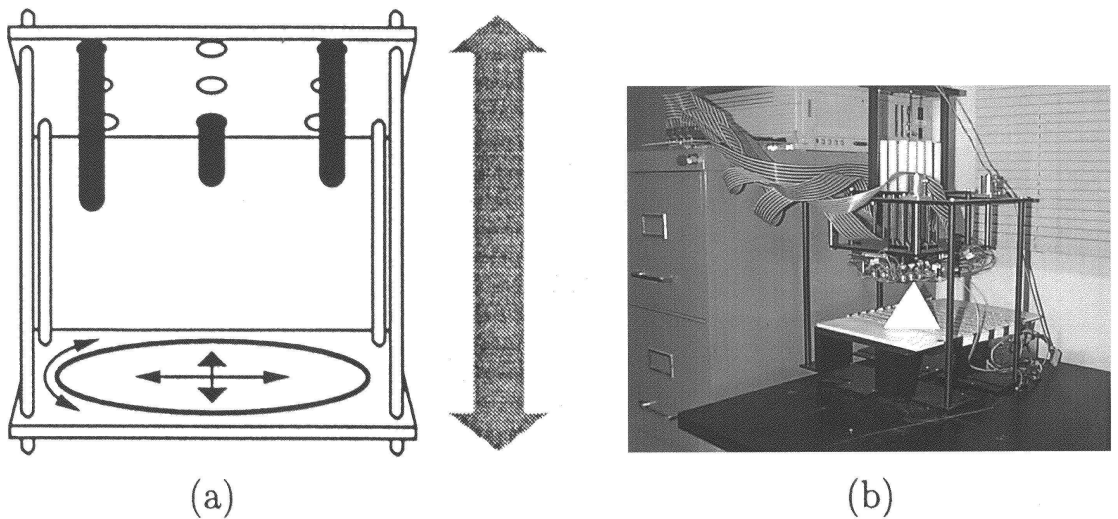


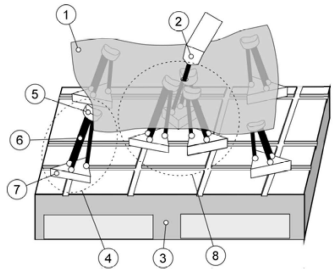
Figure 3. Reconfigurable gripper designed and build by Sudsang *et al.* (2000, Fig. 1): (a) conceptual design and (b) actual prototype.

positioned more accurately than Cartesian robots and have a proven capability to provide large stiffness; they are often applied in modern machining centres (Bi *et al.* 2008, Fleischer *et al.* 2006). Cartesian robots, however, are easier to control and more compact than PKM-based robots. Other principles have been conceived for the design of automatically reconfigurable fixtures. Lee *et al.* (1999) and Izquierdo *et al.* (2009) discuss the fixture layout synthesis for respectively stamping fixtures and assembly fixtures based on SCARA (selective compliant articulated robot arm) with prismatic revolute revolute (PRR) joints. Tol (2003) proposed a design which extends the vise-based modular fixture concept by Wallack and Canny (1994).

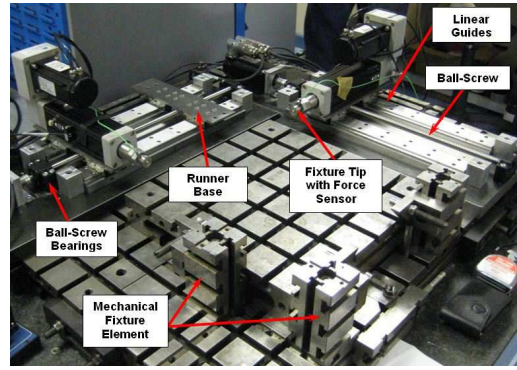
At The University of Nottingham, UK, a more advanced version of the multifinger modules presented in Chan and Lin (1996) has been designed and is described in Papastathis *et al.* (2007), Ryll *et al.* (2008) and Papastathis (2010); their concept is shown in Figure 4(b). Additionally, Ryll (2010) developed a methodology to build a software framework. Papastathis *et al.* (2010) designed a system, shown in Figure 5(a), that has the capability to automatically reconfigure for a family of different high-pressure compressors in aero-engine rotors. Furthermore, a rig was developed by Bakker *et al.* (2011a) for initial tooling evaluation of the application of a fully automated Stewart platform and manual Cartesian adjusters for the assembly of composite wings. This rig is shown in Figure 5(b). Martin *et al.* (2011) provide a detailed discussion on the interface between the metrology and the actuation of the Stewart platform. More advanced 3D concepts of Cartesian robot based fixtures have been developed for the highly automated assembly lines in the automotive industry, e.g. (Anonymous 2006).

3.3. Active Fixtures

Active fixtures, sometimes also referred to as adaptive fixtures, are perhaps the most recent development in fixturing technology. The family of adaptive fixtures includes fixturing systems with elements that can apply variable clamping forces, responding to external stimuli. These fixtures usually deploy clamping elements that incorporate actuation and sensing capabilities, rendering them able to operate in a closed-loop manner. In this sense, they are a logical evolution from both sensor-based and automatically reconfigurable fixtures.

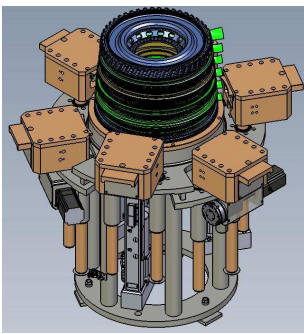


(a) “Conceptual schematic of self-reconfigurable swarm fixture: (1) part; (2) manufacturing equipment; (3) bench; (4) agent; (5) support head; (6) positioning mechanism; (7) mobile bases; (8) concentration of agents in the manufacturing region.” Source: Molfino *et al.* (2009), Fig. 2.

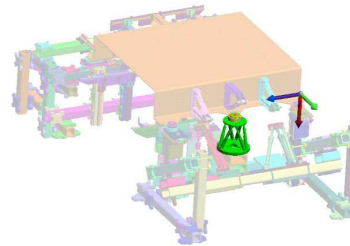


(b) The hardware instantiation of the fully-active fixture prototype, showing the two transport components and the passive locating elements that comprise the fixture. Source: Papastathis (2010), Fig. 3.5.

Figure 4. Design concepts for self-reconfigurable fixtures with the ability to reconfigure during machining process.



(a) Reconfigurable fixture for the assembly of high pressure aero-engine compressors. Source: Papastathis *et al.* (2010), Fig. 2.



(b) Wing assembly fixture developed at The University of Nottingham, taken from: Martin *et al.* (2011), Figure 2.

Figure 5. Reconfigurable fixtures for different aerospace assembly operations.

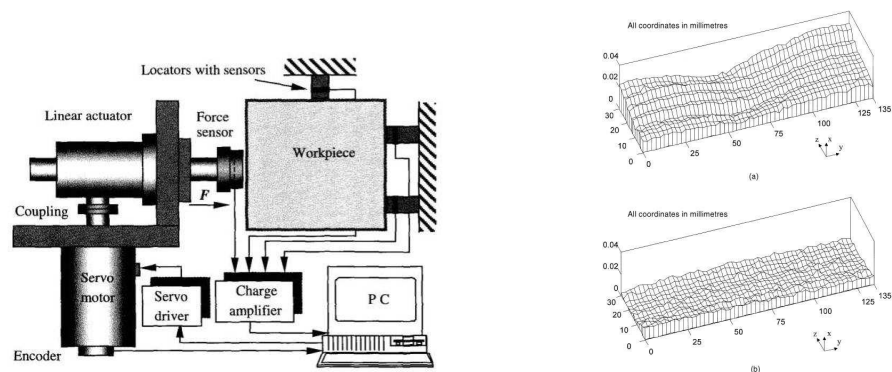
Three approaches, regarding the active control of part-fixture deformation, can be identified in the literature. Firstly, direct compensation for part displacement (position control), secondly, controlling the reaction forces at the locators, and, thirdly, suppressing machine chatter. These approaches will be discussed in the following sections.

Two comprehensive approaches to active fixtures can be found in literature. The eldest is the 'Intelligent Fixturing System' (IFS) developed at the National University of Singapore by Nee and coworkers (Nee *et al.* 2000, 2004). The schematic design is shown in Figure 6(a). The design of the IFS starts after determining the optimal placement and clamping order (Tao *et al.* 1999b) and the optimal clamping forces (Tao *et al.* 1999a). Wang *et al.* (1999) propose to calculate the optimal clamping forces for the IFS off-line, i.e. beforehand, and then use these calculated forces in the real world. Additionally, a proposal for a simple model-based online control of the clamping forces was made (Wang *et al.* 1997). The clamping force in the Singapore IFS is generated by a ball screw driven by a permanent magnet DC motor (Mannan and Sollie 1997). For extra accuracy the ball screw is controlled by a cascaded controller that compares the clamping force with the actuator displacement multiplied by a constant stiffness gain. Not explicitly drawn in Figure 6(a), the clamping force is monitored by force sensors and position control is used to obtain extra accuracy in the position of the tip of the clamp as force and static displacement are proportional to the effective stiffness of the part-fixturing system. Nee *et al.* (2004) apply system identification to establish models for the dynamic control of the IFS, contrary to the proposals by Wang *et al.* (1997, 1999). In Figure 6(b) it can be observed that the approach by Nee *et al.* shows a promising increase of surface quality after machining, this increase has also been observed in the experimental results presented in Papastathis (2010).

The second approach is formed by the concepts developed at The University of Nottingham. Firstly, the design by Papastathis *et al.* (2007), Ryll *et al.* (2008), shown in Figure 4(b), is also used for control of the reaction forces. In Papastathis (2010) and Papastathis *et al.* (2007) a further description of the concept of an intelligent fixturing system, that incorporates active fixture elements and possesses the additional ability to automatically reconfigure, is given. This fixture utilises position and force feedback sources to actively adapt the clamping forces it applies and to autonomously change its set-up, according to the geometry of the workpiece. This approach provides the added capability to change the position of the fixturing elements throughout the manufacturing process. This strategy leads to increased local stiffness of the workpiece around the area where the machining process takes place (Papastathis 2010). The model-based control

design of fixture is reviewed in Sections 4.2.2 and 5.

Finally, Papastathis *et al.* developed an active fixture for the assembly of the high pressure (HP) compressor of the Trent family of Rolls-Royce aero-engines (Papastathis *et al.* 2010). The fixture deploys a series of DC-motor and stepper motor-based linear and rotary actuators in a radial formation. The developed fixture uses quadratic encoders as position feedback sources and strain gauges to monitor and control the clamping forces applied by the fixture. Apart from applying varying clamping forces and controlling them to reject external disturbances, the fixture has the ability to autonomously reconfigure. As a result, the same fixture can be used for the assembly of the HP compressor rotor of five different aero-engine types.



(a) Schematic architecture active fixture developed by Nee *et al.*, taken from: Nee *et al.* (2004), Fig. 6.14.

(b) Measured machined surface profiles, under (a) passive clamping and (b) active clamping. Source: Nee *et al.* (2000), Fig 7.

Figure 6. Concepts of force-controlled fixtures.

Another famous example of adaptive fixturing was developed by Chakraborty *et al.* (2001a,b). This fixture uses a Coordinate Measurement Machine (CMM) to probe important features on automotive engine blocks. This information is employed to identify the exact position and orientation of the surfaces to be machined. A micro-positioning base is adopted to reposition the workpiece to its ideal location.

Bukowski *et al.* (2008) developed a concept that utilises stepper motor actuators playing the role of the active fixture clamps, as shown in Figure 7. Laser and inductive sensors are used to detect large and small workpiece displacements, respectively. Furthermore,

the proposed active fixture bears force sensors to monitor the applied clamping forces and vision sensors that allow for establishing the position of the workpiece relative to the reference frame of the fixture.

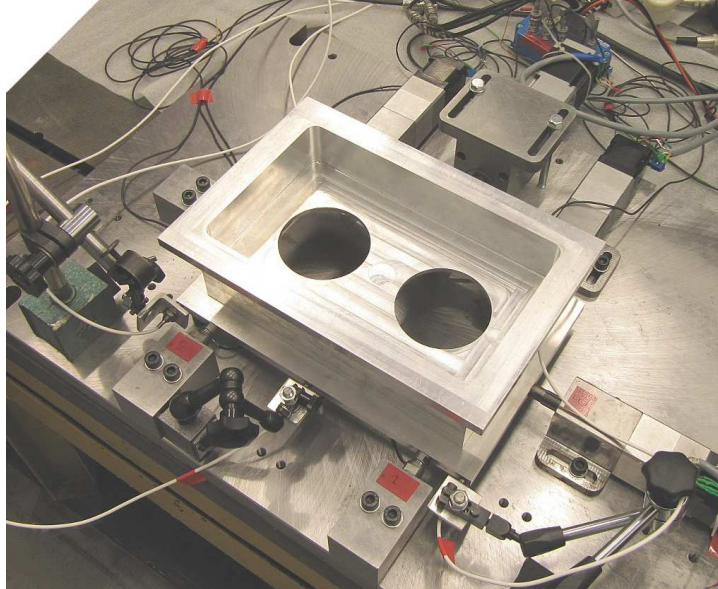


Figure 7. Active fixture designed and built by Bukowski *et al.* (2008). Source: Grochowski *et al.* (2010), Figure 10(b).

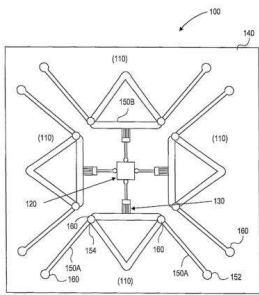
Yamaguchi *et al.* (2010) describe an active assembly fixture consisting of 4 two-segment arms of which the first segment is actuated along its axis. The fixture can position parts onto a certain location, making use of vision, force sensors and inverse kinematics. Zhang *et al.* (2009a) proposed a device to be applied in a modular welding fixture that can compensate for variation in part dimensions. Furthermore, Park and Mills (2005) developed a robot arm with an active gripper able to damp-out vibrations and to compensate for static deformation due to gravitational forces in metal sheet assemblies.

Wiens *et al.* (2010) developed a concept for a force-controlled fixture for meso-scale manufacturing, which is shown in Figure 8(a). Similar to the concept by Yamaguchi *et al.* (2010), the fixture consists of four fixels that can be used to position and orientate the workpiece. The fixel consists of a monolithic four-bar PKM mechanism utilised for active force control and part manipulation.

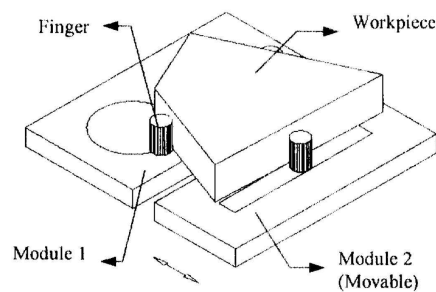
Velíšek *et al.* (2008) developed an intelligent pneumatic clamping device that is aware of both the presence of a part (loaded condition) and the clamp location. The clamps

work simultaneously and in opposite directions, an external cassette is needed to load and hold the part.

Du and Lin (1998) developed a prototype of an automatically reconfigurable fixture for planar objects, consisting of three pins that can be repositioned. One pin can be repositioned with a Cartesian coordinate based mechanism and the two other pins can be repositioned with a rotary table based mechanism, as shown in Figure 8(b). The pin on the moveable module, see Figure 8(b), is used to clamp the part onto the two locators. Du *et al.* (1999) applied an online measurement of the workpiece stiffness in the fixture during machining to control the clamping forces.



(a) Adaptive fixture concept developed by Wiens *et al.*. Source: Wiens *et al.* (2010), Fig. 1.



(b) Three fingered reconfigurable fixturing system presented in Du and Lin (1998), Fig. 1.

Figure 8. Concepts of force-controlled fixtures.

The concept described by Tol (2003) is based on that of Wallack and Canny (1994) and Du and Lin (1998), and uses 4 pins and the Cartesian robot concept instead of two rotating disc elements.

Mc Keown (2009) developed and tested reactive programmable bed of pins fixture for aerospace tooling, where a suction cup mounted on top of each pin is used to pull the metal sheet assembly on the fixture during a stir welding operation.

Adaptive fixtures present numerous advantages. They offer a better understanding of the effect that fixtures have on the manufacturing process outcome and the possibility to adapt the fixture parameters to optimise the results. In essence, adaptive fixtures aim at eliminating the errors caused by the fixturing process and affect the quality of the end-result. In some cases, reconfigurability has been combined with adaptiveness to

produce a flexible and highly-performing solution. The drawback of adaptive fixtures is the increased cost associated with the sensory and actuation equipment necessary.

3.3.1. Related Work

3.3.1.1. Baseplate-Based Concepts.

Vibrations originating from workpiece-machine interaction have an adverse effect on the machining quality. One of the strategies taken to improve tool-life and surface finish is to suppress one or more of the dominant modes of vibration by following the vibrations of the tool. An early approach is made by Tansel *et al.* (1995), who designed a fixture for micro-manufacturing, for improved tool-life by suppressing chatter. Rashid and Nicolescu built a grinding table, sometimes referred to as a chuck or pallet, to cancel vibrations in milling (Rashid and Nicolescu 2006). Recently, this approach has started to receive attention in Germany: (Abele *et al.* 2008, Brecher *et al.* 2010). A similar approach is found in the designs for fixtures that are developed for vibration-assisted grinding in micro-manufacturing, see e.g. Zhong and Yang (2004). Contrary to the concepts discussed above, Daniali and Vossoughi (2009) present a concept where the itself fixture is moved on a the baseplate instead of both baseplate and fixture.

Related to the chatter suppression fixture designs are the micro-positioning tables for grinding that can compensate for workpiece deformation due to machining forces (Gao *et al.* 2001, Zhang *et al.* 2006). Another approach has been taken by Culpepper *et al.* (2005), who developed an eccentric ball-shaft-based positioning-table fixture concept, where the balls are actuated by ball-screw actuators to increase the accuracy of part positioning. In another paper Varadarajan and Culpepper (2007), improved the design by now positioning the balls by means of piezoelectric actuation and flexure bearings.

3.3.1.2. Structural Control-Based Approaches.

This strategy is different from the baseplate-based concepts discussed above in Section 3.3.1.1 in the sense that chatter is not suppressed by means of fixture elements, but by external (extraneous) elements that are directly attached onto the workpiece as is done in modern control of structures. Rashid and Nicolescu (2008) developed a concept with *passive* damping elements, called tuned viscoelastic dampers (TVDs). The

viscoelastic properties of the damper govern the stiffness of the element: it *also* depends on the local velocity of material. Zhang and Sims (2005) attached a piezoelectric element to the workpiece for *active* vibration damping.

4. Dynamics of Part-Fixture Systems

Fixturing devices are in direct contact with the processed workpiece, greatly affecting its dynamic response. Designing better performing and more efficient fixturing systems requires an in depth understanding of the effects they have on the workpiece behaviour and, therefore, the process outcome. As a result, the interaction between fixture and workpiece has received significant attention.

4.1. *Friction and its Effect on the Workpiece-Fixture System*

Dynamics

One of the aspects of fixturing that has received considerable research attention is the friction at the contact points between the fixture and the workpiece. Friction affects the dynamic behaviour of the system and is dynamically affected by the response of the fixture-workpiece system to external dynamic loads. The presence of friction increases the stability of the system and also helps dampen the vibrations experienced by the fixture and the workpiece during dynamic loading conditions. Hurtado and Melkote (1999) aimed at experimentally establishing the coefficient of static friction between a cast aluminium workpiece and oxide-coated steel fixture elements, when excited by dynamic loading. A series of factors and their effects were investigated. These included the normal pre-load forces (clamping forces), the frequency of excitation in both normal and tangential directions, and the vibration amplitude in the normal and tangential directions.

Fang *et al.* (2002) examined the damping effect of friction on the stability of the fixture-workpiece system under machining conditions. More specifically, they formulated a model that included the vibration of the workpiece and the fixturing elements, which was solved using the finite elements method. It was observed that at specific levels of clamping forces, a “locking” effect is starting to emerge, significantly reducing the relative motion between the workpiece surface and the fixturing element. It should be noted that, in the case of

multiple contact interfaces, this locking effect does not emerge simultaneously on all contacting points, but it appears sequentially.

Motlagh *et al.* (2004) utilised the Armstrong non-linear friction model to improve the model developed by Fang *et al.* (2002). The addition of the Armstrong friction model renders the overall model able to converge to a solution even for high clamping forces. This is not possible with the model in (Fang *et al.* 2002). The proposed approach enables the study of pre-sliding and micro-sliding at the fixture-workpiece contact points.

4.2. *Modelling of Fixture and Workpiece Considering their Dynamic Interaction*

Another area that has significantly attracted the attention of the research community is that of the modelling of fixture-workpiece systems and their dynamic behaviour. Models for both passive and active fixture systems have been presented.

4.2.1. *Passive Fixture Systems*

Mittal *et al.* (1991) created a model for the dynamic analysis of the fixture-workpiece system. Their approach is based on the finite element method and the Dynamic Analysis and Design System (DADS) computer code. In this approach the workpiece is treated as rigid. The machining forces and torques are treated as having constant or linearly-varying magnitude. The fixturing elements are simulated as lumped, translational spring-damper-actuator (TSDA) elements. In this way, the local flexibility at the contact points between the fixture and the workpiece is captured. The stiffness in the TSDA elements is treated as linear and the actuator part of the TSDA element is approached as a constant clamping force. This model allows for the separation between workpiece and fixture. The model was used to evaluate the system stability and the effects of clamping sequence and locator arrangement on the machining accuracy of the workpiece. It was shown that the relative placement of locators and clamps has a greater impact than the absolute placement of the locators alone. The sequence of application of the clamps was also observed to have a significant impact on the end result. The authors of this work also pointed out the utility of obtaining the vibration characteristics of the system, as this could help to design a fixture that can reduce surface finish variations.

Yeh and Liou (1999) treated the fixture-workpiece system solely through the stiffness at the contact points. For this they proposed the use of virtual springs to simulate the interaction between the workpiece and the fixture. The mass of the virtual springs and the damping are considered negligible. A modified version of the Hertz contact theory was used to establish the stiffness of the virtual springs. Spring constants that stemmed from the above two models are incorporated in a FE model, which is used to calculate the natural frequencies and the frequency response of the simulated system. Experimental modal analysis results proved the validity of the proposed modelling approach.

Behzadi and Arezoo (2002) followed a similar approach to model the dynamic behaviour of a fixture-workpiece system. The workpiece is considered perfectly rigid and the rigidity of the fixturing elements is represented through spring-damper elements. The entire system is regarded to be linear. The developed model was implemented to investigate the effect of support elements on the flatness and roughness of a machined surface.

Deiab and Elbestawi (2004) proposed a more comprehensive model of the fixture and workpiece system. This model treats both the workpiece and the fixture elements as flexible. The interaction at the contact points is modelled through spring elements enhanced with a modified version of Coulomb's law of friction. This aims at reflecting the effects of friction. The model also integrates a three-dimensional model of the workpiece, the geometry of the cutting edge of the tool, and modal characteristics of the machine tool. In this way, the dynamics induced by the cutting forces can be accounted for in the model, allowing for a more accurate calculation of the workpiece and the fixture dynamic deformations. The model was used to evaluate the effects of friction, location of fixture elements and contact stiffness on the machining process outcome.

Liao and Hu (2001) developed a Finite Element Analysis-based model of the fixture-workpiece system, which treats the workpiece, the fixture elements and the fixture base as flexible. The dynamic compliance of the workpiece and the contact stiffness characteristics are also reflected in the model. The approach can take into account the deflection experienced by the fixture and the workpiece due to the static clamping loads, instantaneous machining forces and the forced vibrations caused by the dynamically changing amplitude of the machining forces. The model is used to predict the surface flatness of

fixtures parts under dynamic machining conditions.

Phuah (2005) and Ratchev *et al.* (2005, 2007) also used the finite element approach to describe the dynamic behaviour of fixture-workpiece systems undergoing a grinding process. In this work the workpiece is treated as a deformable solid and simulated in commercial FE software. The fixturing elements are introduced into the model as spring and damper elements. The stiffness profile of these elements was determined experimentally. The changing point of application of the dynamic machining loads is captured in the work, however, this is achieved in a pseudo-static manner.

Deng (2006) worked on incorporating the effects of material removal due to a machining process on the dynamic behaviour of a workpiece. As in some of the previously described cases, this work treats the fixturing elements and the workpiece as deformable solids. The fixture base, however, is considered to be rigid. The mass removal effects were incorporated by considering both the mass characteristics of the workpiece and the rate of change of its inertia. The former was obtained through the geometric model of the workpiece in various phases of the machining process using the 3D modelling engine ACIS. The mass reduction rate was calculated through the forward finite differences method. The stiffness characteristics of the workpiece are obtained using the FEA software ANSYS. The damping characteristics of the workpiece and fixture elements are not taken into account. Finally, the fixture-workpiece interaction is represented through a set of spring constants acting in all three translational Cartesian directions. This representation accounts for the stiffness of the fixture elements and the stiffness of the contact. The model was used to investigate the dynamic stability of the system throughout the manufacturing process. It was also used to optimise the design of the fixturing process, and more specifically the applied clamping loads.

A simplified model of the above, one that treats the workpiece and the fixturing elements as rigid, was also established by Deng and Melkote (2005). This model includes the material removal effects and accounts for the dynamic nature of the machining loads. The model was developed using analytical expressions and the authors investigated the dynamic stability of the system and the effects of clamping forces. Most authors, see e.g. Govender (2001), Kaya and Öztürk (2003), Nikov (2004) and Rai and Xirouchakis (2008), propose the use of special elements in the finite element environment to take care of the

material removal. In addition, Deng (2006) studies the influence of material removal on fixturing stability and proposes to optimise the clamping by taking into account the material removal. Zhang *et al.* (2009b) propose to apply matrix perturbation techniques to update the mass and stiffness matrices to accommodate for material removal.

4.2.2. Active Fixture Systems

In all above cases, the fixturing elements are treated as passive components. Locating elements are at best regarded as deformable bodies that present a reaction force when external loads are applied on the workpiece. Clamping elements present the same behaviour, but they are also granted the ability to apply constant forces on the workpiece. However, with the advent of active fixtures this approach is no longer adequate. The fixture elements can actively react to external forces, automatically adapting their position, reaction and clamping forces. The dynamic response of the fixturing elements of active fixtures should therefore be taken into consideration when modelling such fixturing systems. Bakker *et al.* (2008b) were perhaps the first to integrate the dynamic behaviour of active fixture elements to the model of a fixture-workpiece. In this work the active fixture elements take the form of hydraulic actuators, whose response is reflected by a first-principle-based analytic model. The workpiece is approached as a concentrated mass object. The compliance of the fixturing element and the workpiece are modelled as spring and damper pairs. The forces that are exerted on the system present time-varying amplitude. The developed model was used to theoretically investigate the performance of position-feedback and force-feedback control strategies, with various controller designs. Bakker *et al.* used the same modelling approach to investigate the performance of control strategies and controller designs for a fixture-workpiece system with piezoelectric actuators (Bakker *et al.* 2008a). The workpiece is again treated as a concentrated mass-spring-damper system, connected to the active fixturing element through a lever mechanism.

Expanding the previous models, Bakker *et al.* (2009a) proposed a methodology through which the dynamic behaviour of an active fixture-workpiece system can be extracted. The active fixture elements in this work are based on hydraulic actuation with closed-loop operation. The workpiece is described through a reduced finite elements model.

The behaviour of the modelled system under various control strategies was investigated. The above methodology was also applied to establish the fixture-workpiece system of a thin-walled, box-shaped workpiece fixated by an active fixture with electromechanical actuators as clamps (Bakker *et al.* 2009b). Permanent magnet synchronous motor (PMSM) actuators were assumed. These were modelled using the first-principle equations that apply for DC motors. Step forces were used as the source of excitation of the system. Different control strategies were investigated for their performance in minimising the workpiece displacement.

Moreover, in Bakker *et al.* (2011b) and Bakker (2010), the aforementioned methodology was implemented to simulate the behaviour of a Nozzle Guide Vain (NGV) workpiece being processed by grinding. A reduced model of the workpiece was coupled with an analytical model of piezoelectric active clamps, operating in closed loop. The dynamic amplitude and moving nature of the forces exerted on the workpiece by the grinding process were also included.

Papastathis (2010) and Papastathis *et al.* (2012) expanded the study on moving loads in combination with an experimental validation of the in-depth modelling of active electromechanical fixturing elements coupled with FEA models of thin-walled components. Additionally, Papastathis (2010) investigated an optimisation strategy for the dynamic replacement of the fixturing elements, which allows a fixture structure to be modelled automatically reconfigurable during the machining process. To the authors' best knowledge this is the first time this paradigm has been analysed in an extensive manner.

Nee *et al.* (2004) presented another approach to modelling the active fixture-workpiece system. This approach is based on system identification principles and the establishment of a parametric Autoregressive-Moving Average (ARMA) model. The least squares technique was proposed as the means of calculating the unknown parameters of the ARMA model. As this model is extracted from experimental data, it reflects all the parameters that contribute to the response of the system.

Finally, a special mention should be given to the following research activities, despite the fact that both treat the fixture workpiece system as quasi-static. Grochowski *et al.* (2010) use commercial FEA software to model the workpiece. The active elements of the fixture, which are composed of stepper-motor actuators, are modelled using first

principles. Their closed-loop operation, controlled by a PID regulator, is reflected in the developed model. The latter is introduced to the FEA model of the workpiece through subroutines implemented in the Fortran77 programming language. The model was used to evaluate the performance of a system in controlling the position of a point on a beam workpiece that experiences deflection due to externally applied forces. The point whose position is controlled does not coincide with the contact point between the fixture and the workpiece.

Nee *et al.* (2004) do not reflect the dynamic behaviour of the active elements of their system in their FE model of the workpiece. The fixture elements are represented as spring elements. For every time step for which the FE model is solved, the clamps can apply forces with different amplitude and different point of application. This way, the model reflects the ability of the fixture to dynamically adjust the position of the clamps and the clamping forces it exerts. This is the first and only instance where the effects of clamps that constantly change their positions during the manufacturing process are mentioned.

4.3. Fixture Design Methods Accounting for System Dynamics

In many cases, dynamic models of the fixture-workpiece systems have been used to assist the design of the fixture. Daimon *et al.* (1985) formulated a fixture design method, based on the dynamic behaviour of a fixated workpiece. They used finite element simulation and/or experimental modal analysis data to evaluate the dynamic compliance of the workpiece under a certain fixture layout. The proposed method can be employed to evaluate the positions where additional supports would reduce the dynamic compliance of the workpiece to acceptable levels. Similar is the work by Mittal *et al.* (1991), in this approach the fixture elements were simulated as sets of springs and dampers. The latter were treated as having constant stiffness and damping coefficients, respectively. The method was trialled on thin-walled cast iron and steel box-like workpieces.

Padmanaban and Prabhakaran (2008) proposed another design method, also based on the dynamic behaviour of a fixture-workpiece. It uses Ant Colony and Genetic Algorithms to minimise the dynamic elastic deformations experienced by a workpiece, excited by harmonic forces. In this work the workpiece is treated as deformable, but the fixture itself is rigid. The objective function of the problem, generated by formulating the problem

through finite element principles, is solved using the modal superposition method. The workpieces for which the method was tested are two-dimensional and are excited by purely harmonic forces acting in the plane of the workpiece.

Deiab (2006) used the finite element analysis to investigate the effect that the position of supporting elements has on the dynamic response of a workpiece undergoing an end-milling operation. This model includes factors like cutting edge geometry, process parameters, fixture layout, and others. Both the workpiece and the fixture elements are considered flexible. The model was used to identify the fixture layout that increases the stability of the system and reduces the maximum vibration amplitude experienced by the workpiece under dynamic excitation. This study concentrates only on the positioning of passive support elements.

Li and Melkote (2001) used a lumped mass and stiffness model to describe the dynamic response of the fixture-workpiece system. The fixturing elements are represented as a set of springs, two in the tangential and one in the normal direction to the surface of the workpiece at the point of contact. Damping and slippage at the contact points were not taken into account. The same holds true for the moving nature of the point of application of machining forces. An iterative algorithm was used to establish the fixture layout and clamping forces that resulted in the lowest positional/location error of workpiece.

Deng (2006) and Deng and Melkote (2006) implemented the model already discussed in Section 4.2.1, to optimise the clamping forces that are applied by the fixture per tool pass during the machining process. As already mentioned, the model behind this fixture design method considers the dynamic response of the fixture-workpiece system, whilst also incorporating the effects of the material removal to the dynamic response of the system. The optimisation problem is solved using the Particle Swarm Optimisation technique.

As already expounded in Section 4.2.2, Papastathis (2010) proposed an optimisation strategy for the dynamic replacement of fixture elements in the design phase of active and in-process reconfigurable fixtures.

5. Control Strategies for Active Fixtures

Another research area that is of great importance in this field is that of the control strategies that have been proposed for the regulation of the operation of active fixtures. Mannan and Sollie (1997) proposed the cascaded position/force control algorithm for the operation of active clamping elements. This method utilises two feedback sources, namely a force sensor and a position sensor. The control loop implements two controllers: one implemented by means of a motion control card, and the other implemented by means of software. The former is a PID (proportional-integral-derivative) controller and the latter is a simple proportional controller. The controlled variable in this work was the force applied by the clamping elements of a prototype active fixture.

Nee *et al.* (2004) used the same approach with a slight variation in their application. More exactly, the proportional controller in the force-feedback loop (external loop) that was utilised by Mannan and Sollie was replaced by a simplified version of the Generalised Minimum Variance (GMV) self-tuning controller.

Du *et al.* (1999) described the utilisation of two separate control strategies to regulate the positioning and force application tasks of a prototype three-fingered intelligent fixture. The direct position feedback was used to control the positioning actions of the fixture. The feedback source for this loop was an optical encoder mounted on the axis of a DC motor. The direct force feedback approach was used to control the forces exerted by the fixture on a thin-walled cylindrical workpiece. Strain gauges were utilised as the feedback source for this loop. A digital controller was in charge of regulating the response of the fixture. No further detail were given on the characteristics of this controller.

Bakker *et al.* (2008a,b, 2009a,b) examined the effect of different control schemes on the response of the fixture-workpiece system. In detail, both force- and position-feedback with various controller designs were examined. The goal was to investigate which of the above schemes leads to a system that reacts to external loads in such a way that the workpiece displacement is minimised. The direct force-feedback and the direct position feedback algorithms were used. This work showed that position feedback leads to a system that minimises the unwanted behaviour of the workpiece.

Papastathis (2010) investigated experimentally the performance of two different control strategies for active fixturing elements based on PMAC actuators. The first one is the cascaded position/force control strategy, and the second is the direct-force control strategy. Results showed that the latter strategy presents faster response to command inputs, although high overshooting was a drawback of this method.

Grochowski *et al.* (2010) applied a simple position-feedback loop architecture to control the displacement of a cantilever beam workpiece by using stepper motors as active fixture elements. A PID regulator was used to control the response of the system.

Most of the previously described approaches have the objective to minimise workpiece displacement and deformation under clamping either by controlling the applied clamping forces or by controlling the position of the tip of the active clamping elements. Looking into a possible capability of active fixturing systems, Rashid and Nicolescu (2006) investigated the ability to actively control the vibration experienced by a workpiece undergoing end-milling processing. To achieve this, their palletised active fixture deploys three-component force sensors and piezoelectric actuators housed in the baseplate of the palletised fixture. The authors of this worked implemented the filtered input least-mean squares (FXLMS) algorithm to control the output of the actuators.

6. Conclusions and Future Developments

6.1. Conclusions

A review of the developed fixturing technologies, as presented in this paper, reveals that performance and flexibility are the driver behind the different fixturing concepts that have been proposed. Flexibility is the point of focus in many cases. Conformable fixtures, modular fixtures and phase-change fixtures are examples of highly flexible fixturing solutions. In most recent years, however, fixturing concepts have been developed with performance in mind. This is reflected in the increased attention that active fixtures have received during the past fifteen years. Fixture concepts behind which the combination of increased performance and flexibility is the driver have yet to be proposed.

Furthermore, the active fixture solutions thus far concentrate on the application of dynamically-adjusted clamping forces. Fully-active fixtures, which can vary the ampli-

tude and point of application of clamping forces throughout the manufacturing process have mostly been suggested and discussed on a hypothetical basis. Apart from the work by Papastathis (2010), hardware implementation of the concept of fully-active fixtures has not been encountered. This fixturing technology not only promises enhanced performance, but could also combine it with high levels of flexibility.

Apart from fixture concepts, another subject within the field of fixturing that has received considerable amount of attention is the investigation and modelling of the effects of fixtures on the behaviour of the workpiece. This of course directly relates to increased performance of fixturing solutions. Understanding how the fixture affects the outcome of a process is the key to design better performing fixtures. Friction and contact stiffness at the fixture and workpiece interface points, and how these affect the response of the workpiece to external stimuli, have been the focal point for many researchers. A series of modelling approaches, each with its own assumptions, simplifications and limitations, has attempted to enhance understanding of the fixture-workpiece system. The accurate simulation of the static and dynamic response of the fixture and workpiece system to the clamping forces and the externally applied forces has been the main goal of the proposed models. These models can be used for verifying the performance of a fixture in terms of its stability and the workpiece deformations, bypassing the need for building cost-intensive prototypes.

Additionally, the developed models have been used as means of designing better performing fixtures. The careful placement of locating, supporting and clamping elements around the workpiece could amplify stability and reduce deformations and vibrations, experienced by the workpiece. Also, a fixture that performs as intended, with the minimum number of fixturing elements around the workpiece, helps improve accessibility.

6.2. *Prospective Future Trends*

Integration with General Fixture Design

An integration is needed of the design methodology for active fixturing systems with more general Computer Aided Fixture Design and Fixture and Production Planning. The model-based design methodology for the controllers presented in Bakker (2010),

Bakker *et al.* (2009a, 2011b) and Papastathis (2010) enables the control design engineer to work almost in phase with the hardware design, but to date there is no unified design methodology for intelligent fixturing systems.

Such a design methodology will rely heavily on the mechatronic design approach which has been successfully applied for the design of high-tech precision machinery. Mechatronics is a multidisciplinary and multiphysics approach by nature, as it joins the design and analysis of mechanical, control, electronic and software systems. This mechatronic design approach will involve the utilisation of established tools developed in the area of structural mechanics for the mechanical analysis of the part-fixture system. Especially, for the fixtures designed for compliant parts, e.g. aerospace components, it is paramount that the flexibility of the workpiece is taken into account during the fixture-design process. Currently, in many of the approaches found in the literature, the workpiece is often assumed to be rigid. Another aspect where the multidisciplinary mechatronic design approach can bear its fruits is when model updating techniques developed in the area of structural mechanics are applied in a real-time model to deal with the material removal during the machining process.

Labouring further on the mechatronic design approach, the control systems developed within the area of modern control theory, such as \mathcal{H}_∞ , \mathcal{H}_2 and μ -synthesis, predictive control, adaptive and robust control should be used in the design of controllers for active fixtures. Especially since fixture designs for real industrial parts typically consist of multiple clamps, which should be controlled simultaneously.

Integration with High-Level Shop Floor Control

For industrial application, the design of active fixture hardware and controllers will have to be integrated with the high-level control that manages the automated production systems in the workshop. The low-level control of active fixturing systems will have to deal with the automatic loading of a workpiece into the fixture. Furthermore, between different jobs, or even during the job, an intelligent fixture can be reconfigured, requiring new low-level control settings for the clamping forces.

Extension of Active Fixturing into Other Fields

Much of the fixturing research is carried out in the field of machining fixtures. This is reflected in the field of active fixturing research. However, the application of active fixturing systems can be wider than machining fixtures only. The predicted growing demand for air travel will result in an increase in demand for new air planes. Meanwhile, the skilled labour force needed for the aircraft build is shrinking, forcing aerospace manufacturers into automation. If that trend persists, significant research and development activities are needed to develop assembly fixtures that meet the stringent tolerance demands in aerospace, and are e.g. suitable for use with composites at the same time, or capable of working with families of aero-engine components. Some initial work in these areas has been carried out by Bakker *et al.* (2011a), Jayaweera *et al.* (2011) and Papastathis *et al.* (2010).

Furthermore, given the increasing importance of nano/meso/micro-manufacturing for the industry sector in the developed world, it would be interesting to see the methodology established here, expanding to micro-scale and smaller. Already, some work has been undertaken to develop active fixtures for this scale, e.g. by Wiens *et al.* (2010). Other fields for the extension of general fixturing research mentioned by Nee *et al.* (1995) and Wang *et al.* (2010) are welding and heat treatment fixtures.

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References

Abele, E., *et al.*, 2008. Development and Design of an Active Work Piece Holder Driven by Piezo Actuators. *Production Engineering: Research and Development*, 2 (4), 437–

- 442.
- Anonymous, 2006. Intelligent Robots Take the Tooling out of Nissan's Sunderland Floor Pan Assembly Operation. *Industrial Robot: An International Journal*, 33 (5) Mini feature.
- Arzanpour, S., *et al.*, 2006. Flexible Fixture Design with Applications to Assembly of Sheet Metal Automotive Body Parts. *Assembly Automation*, 26 (2), 143–153.
- Bakker, O.J., 2010. Control Methodology and Modelling of Active Fixtures. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Bakker, O.J., *et al.*, 2011a. Fixturing and Tooling for Wing Assembly with Reconfigurable Datum System Pickup. *SAE 2011 AeroTech Congress & Exhibition paper 2011-01-2556*, October., Toulouse, 1–8.
- Bakker, O.J., Popov, A., and Ratchev, S., 2008a. Control of a Workpiece Holder with Piezo-Electric-Mechanical Actuation. *Journal of Machine Engineering*, 8 (3), 17–28.
- Bakker, O.J., Popov, A.A., and Ratchev, S.M., 2008b. Investigation into Feedback Control of Part-Fixture Systems Undergoing Dynamic Machining Forces. *In: P. Sas and B. Bergen, eds. Proceedings of ISMA2008*, September. Leuven (Heverlee): Katholieke Universiteit Leuven - Departement Werktuigkunde, 131–140.
- Bakker, O.J., Popov, A.A., and Ratchev, S.M., 2009a. Fixture Control by Hydraulic Actuation Using a Reduced Workpiece Model. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, 223, 1553–1566.
- Bakker, O.J., Popov, A.A., and Ratchev, S.M., 2009b. Model-Based Control of an Advanced Actuated Part-Fixture System. *In: Proceedings of 2009 ASME International Manufacturing Science and Engineering Conference*, MSEC2009-84175, October.
- Bakker, O.J., *et al.*, 2011b. Model-Based Control of an Active Fixture for Advanced Aerospace Components. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 225 (1), 35–51.
- Behzadi, M.R. and Arezoo, B., 2002. Static and Dynamic Models for Predicting the Effects of Supports on Machining Flatness and Roughness. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, 216, 735–742.
- Benhabib, B., Chan, K.C., and Dai, M.Q., 1991. A Modular Programmable Fixturing

- System. *Transactions of the ASME – Journal of Engineering for Industry*, 113, 93–100.
- Bi, Z.M., *et al.*, 2008. Development of Reconfigurable Machines. *International Journal of Advanced Manufacturing Technology*, 39, 1227–1251.
- Bi, Z.M. and Zhang, W.J., 2001. Flexible Fixture Design and Automation: Review, Issues and Future Directions. *International Journal of Production Research*, 39 (13), 2867–2894.
- Boyle, I., Rong, Y., and Brown, D.C., 2011. A Review and Analysis of Current Computer-Aided Fixture Design Approaches. *Robotics and Computer-Integrated Manufacturing*, 27, 1–12.
- Brecher, C., *et al.*, 2010. Chatter Suppression with an Active Workpiece Holder. *Production Engineering: Research and Development*, 4 (2-3), 239–245.
- Bukowski, A., Kwasny, W., and Jedrzejewski, J., 2008. Mechatronic Approach to the Development of an Intelligent Fixturing Device Test-Bed. *Journal of Machine Engineering*, 8 (3), 66–76.
- Cecil, J., 2001. Computer-Aided Fixture Design - A Review and Future Trends. *International Journal of Advanced Manufacturing Technology*, 18, 790–793.
- Chaipradabgiat, T., Jin, J., and Shi, J., 2009. Optimal Fixture Locator Adjustment Strategies for Multistation Assembly Processes Locator adjustment. *IIE Transactions*, 41 (9), 843–852.
- Chakraborty, D., De Meter, E.C., and Szuba, P.S., 2001a. Part Location Algorithm for an Intelligent Fixturing System Part 1: System Description and Algorithm Development. *Journal of Manufacturing System*, 20 (2), 124–134.
- Chakraborty, D., De Meter, E.C., and Szuba, P.S., 2001b. Part Location Algorithm for an Intelligent Fixturing System Part 2: Algorithm Testing and Evaluation. *Journal of Manufacturing System*, 20 (2), 135–148.
- Chan, K.C. and Lin, C.S., 1996. Development of a Computer Numerical Control (CNC) Modular Fixture-Machine Design of a Standard Multifinger Module. *International Journal of Advanced Manufacturing Technology*, 11, 18–26.
- Chang, M., Kob, M., and Park, S.C., 2011. Fixture Modelling for an Automotive Assembly Line. *International Journal of Production Research*.
- Culpepper, M.L., Varadarajan, K.M., and DiBiasio, C., 2005. Design of Integrated Ec-

- centric Mechanisms and Exact Constraint Fixtures for Micron-Level Repeatability and Accuracy. *Precision Engineering*, 29, 65–80.
- Daimon, M., *et al.*, 1985. Study for Designing Fixtures Considering Dynamics of Thin-Walled Plate- and Box-Like Workpieces. *CIRP Annals – Manufacturing Technology*, 34 (1), 319–322.
- Daniali, M.M. and Vossoughi, G., 2009. Intelligent Active Vibration Control of Constrained Manipulators in Robotic Deburring. *In: Proceedings of ICIMA2009 International Conference on Industrial Mechatronics and Automation*, Athens, 76–80.
- Dashchenko, A.I., 2006. *Reconfigurable Manufacturing Systems and Transformable Factories*. Berlin Heidelberg: Springer-Verlag.
- De Meter, E.C., 2004. Light Activated Adhesive Gripper (LAAG) Workholding Technology and Process. *Journal of Manufacturing Processes*, 6 (2), 201–214.
- de Meter, E.C. and Hockenberger, M.J., 1997. The Application of Tool Path Compensation for the Reduction of Clamping-Induced Geometric Errors. *International Journal of Production Research*, 35 (12), 3415–3432.
- Deiab, I.M., 2006. On the Effect of Fixture layout on Part Stability and Flatness During Machining: A Finite Element Analysis. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, 220, 1613–1620.
- Deiab, I.M. and Elbestawi, M.A., 2004. Effect of Workpiece/Fixture Dynamics on the Machining Process Output. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, 218, 1541–1553.
- Deng, H., 2006. Analysis and Synthesis of Fixturing Dynamic Stability in Machining Accounting for Material Removal Effect. Thesis (PhD). Georgia Institute of Technology, Atlanta, Georgia.
- Deng, H. and Melkote, S.N., 2005. Analysis of Fixturing Dynamic Stability in Machining. *In: Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, July, Monterey, California, USA, 869–874.
- Deng, H. and Melkote, S.N., 2006. Determination of Minimum Clamping Forces for Dynamically Stable Fixturing. *International Journal of Machine Tools & Manufacture*, 46, 847–857.
- Denkena, B., Möhring, H.C., and Litwinski, K.M., 2009. Sensing Fixtures for Process

- Monitoring. In: D.T. Pham, E.E. Eldukhri and A.J. Soroka, eds. *Innovative Production Machines and Systems* Manufacturing Engineering Centre, Cardiff University: Whittles Publishing.
- Du, H. and Lin, G.C.I., 1998. Development of an Automated Flexible Fixture for Planar Objects. *Robotics and Computer-Integrated Manufacturing*, 14, 173–183.
- Du, H., *et al.*, 1999. An Approach to Enhancing the Intelligence of a Three-Fingered Automated Flexible Fixturing System by Using Adaptive Control Theory. *Robotics and Computer-Integrated Manufacturing*, 15, 101–110.
- Fang, B., DeVor, R.E., and Kapoor, S.G., 2002. Influence of Friction Damping on Workpiece-Fixture System Dynamics and Machining Stability. *Transactions of the ASME – Journal of Manufacturing Science and Engineering*, 124, 226–233.
- Fleischer, J., *et al.*, 2006. Workpiece and Tool Handling in Metal Cutting Machines. *Annals of the CIRP*, 55 (2), 817–839.
- Gao, Y., Zhang, D., and Yu, C.W., 2001. Dynamic Modeling of a Novel Workpiece Table for Active Surface Grinding Control. *International Journal of Machine Tools & Manufacture*, 41, 609–624.
- Geldart, M., 2002. The Development of an Agile Fixturing Approach for the Encapsulation and Machining of Complex Components. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Govender, E., 2001. An Intelligent Deflection Prediction System for Machining of Flexible Components. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Grochowski, M., Bukowski, A., and Jedrzejewski, J., 2010. Modelling of Mechatronic Workpiece-Fixture System Focusing on Active Compensation of Displacements. In: *Proceedings of the 21st International Computer-Aided Production Engineering Conference (CAPE 2010)* On CD-ROM, Edinburgh, 1–8.
- Gupta, S., Bagchi, A., and Lewis, R., 1988. Sensor Based Fixturing System. In: A. Mittal, ed. *Recent Developments in Production Research*, Amsterdam: Elsevier Science Publishers B.V., 11–16.
- Hameed, R.A., Mannan, M.A., and Nee, A.Y.C., 2004. The Cutting Force Measurement in a Fixturing Setup with Instrumented Locators. *International Journal of Advanced*

- Manufacturing Technology*, 23, 783–793.
- Hargrove, S.K. and Kusiak, A., 1994. Computer-Aided Fixture Design: A Review. *International Journal of Production Research*, 32 (4), 733–753.
- Hazen, B.F. and Wright, P.K., 1990. Workholding Automation: Innovations in Analysis, Design, and Planning. *Manufacturing Review*, 3 (4), 224–236.
- Hurtado, J.N. and Melkote, S.N., 1999. Workpiece-Fixture Static Friction Under Dynamic Loading. *Wear*, 231, 139–152.
- Izquierdo, L.E. *et al.*, 2009. Robust Fixture Layout Design for a Product Family Assembled in a Multistage Reconfigurable Line, *Transactions of the ASME – Journal of Manufacturing Science and Engineering*, 131, 041008-1–041008-9.
- Jayaweera, N., *et al.*, 2011. Flexible Tooling for Wing Box Rib Clamping and Drilling. *SAE 2011 AeroTech Congress & Exhibition paper 2011-01-2639*, October, Toulouse, 1–9.
- Jonsson, M., Kihlman, H., and Ossbahr, G., 2008. Coordinate Controlled Fixturing for Affordable Reconfigurable Tooling. *In: Proceedings of the 2nd CIRP Conference on Assembly Technologies and Systems*, Toronto, 1–11.
- Jonsson, M. and Ossbahr, G., 2010. Aspects of Reconfigurable and Flexible Fixtures. *Production Engineering: Research and Development*, 4, 333–339.
- Kals, H.J.J., van Luttervelt, C.A., and Moulijn, K., 1998. *Industriële Productie, Het Voortbrengen van Mechanische Producten {~Industrial Production, The Manufacturing of Mechanical Products}*. 2nd Diemen: Wegener Tijdschriften Groep In Dutch.
- Kang, X. and Peng, Q., 2009. Recent Research on Computer-Aided Fixture Planning. *Recent Patents on Mechanical Engineering*, 2 (1), 8–18.
- Kaya, N. and Öztürk, F., 2003. The Application of Chip Removal and Frictional Contact Analysis for Workpiece Fixture Layout Verification. *International Journal of Advanced Manufacturing Technology*, 21, 411–419.
- Kleinwinkel, J.W., *et al.*, Toepassen van Slimme Opspanmiddelen {~Application of Smart Fixturing}. , 2006. , Tech-Info-Blad {~Technical Information Publication} TI.06.30, FME-CMW {~Dutch Trade Association for Manufacturing, Metal and Electronic Industry}, Zoetermeer, in Dutch.
- Kong, Z. and Ceglarek, D., 2006. Fixture Workspace Synthesis for Reconfigurable As-

- sembly Using Procrustes-Based Pairwise Configuration Optimization. *Journal of Manufacturing Systems*, 25 (1), 25–38.
- Kurz, K., *et al.*, 1994. Developing a Flexible Automated Fixturing Device. *Mechanical Engineering*, 116 (7), 59–63.
- Lee, J., Hu, S.J. and Ward, A.C., 1999. Workspace Synthesis for Flexible Fixturing of Stampings, *Transactions of the ASME – Journal of Manufacturing Science and Engineering*, 121 (3), 478–484.
- Leopold, J. and Hong, L., 2009. Clamping Modelling: State-of-the-Art and Future Trends. *Industrial Robot: An International Journal*, 36 (3), 249–254.
- Li, B. and Melkote, S.N., 2001. Optimal Fixture Design Accounting for the Effect of Workpiece Dynamics. *International Journal of Advanced Manufacturing Technology*, 18, 701–707.
- Li, B. *et al.* 2010. Variation Analysis and Robust Fixture Design of a Flexible Fixturing System for Sheet Metal Assembly, *Transactions of the ASME – Journal of Manufacturing Science and Engineering*, 132, 041014-1–041014-13.
- Li, Q., 2008. Virtual Reality for Fixture Design and Assembly. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Liao, Y.G. and Hu, S.J., 2001. An Integrated Model of a Fixture-Workpiece System for Surface Quality Prediction. *International Journal of Advanced Manufacturing Technology*, 17, 810–818.
- Mannan, M.A. and Sollie, J.P., 1997. A Force-Controlled Clamping Element for Intelligent Fixturing. *Annals of the CIRP*, 46 (1), 265–268.
- Martin, O.C., *et al.*, 2011. Metrology Enhanced Tooling for Aerospace (META): A Live Fixturing, Wing Box Assembly Case Study. *In: Proceedings of DET2011 7th International Conference on Digital Enterprise Technology*, Athens, 83–92.
- Mc Keown, C.M., 2009. Design, Testing and Validation of a Novel Aerospace Reactive Reconfigurable Tooling System. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Meshreki, M., *et al.*, 2008. Dynamics Modeling and Analysis of Thin-Walled Aerospace Structures for Fixture Design in Multiaxis Milling. *Transactions of the ASME – Jour-*

- nal of Manufacturing Science and Engineering*, 130, 031011–1–031011–12.
- Mittal, R.O., Cohen, P.H., and Gilmore, B.J., 1991. Dynamic Modeling of the Fixture-Workpiece System. *Robotics & Computer Integrated Manufacturing*, 8 (4), 201–217.
- Molfino, R., Zoppi, M., and Zlatanov, D., 2009. Reconfigurable Swarm Fixtures. In: J.S. Dai, M. Zoppi and X. Kong, eds. *Proceedings of the ASME/IFTOMM International Conference on Reconfigurable Mechanisms and Robots*, London, 730–735.
- Motlagh, H.E., Hamed, M., and Nikkhah-Bahramy, M., 2004. Application of the Armstrong Friction Model to Study Dynamic Transient Response in Workpiece-Fixture Systems. *Proceeding of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 218, 737–747.
- Munro, C. and Walczyk, D.F., 2007. Reconfigurable Pin-Type Tooling: A Survey of Prior Art and Reduction to Practice. *Transactions of the ASME – Journal of Manufacturing Science and Engineering*, 129, 551–565.
- Nee, A.Y.C., Senthil Kumar, A., and Tao, Z.J., 2000. An Intelligent Fixture with a Dynamic Clamping Scheme. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, 214, 183–196.
- Nee, A.Y.C., Tao, Z.J., and Senthil Kumar, A., 2004. *An Advanced Treatise on Fixture Design and Planning*. Series on Manufacturing Systems and Technology. Singapore: World Scientific Publishing Company.
- Nee, A.Y.C., Whybrew, K., and Senthil Kumar, A., 1995. *Advanced Fixture Design for FMS*. London: Springer-Verlag.
- Nikov, T.T., 2004. Material Removal Simulation in Machining of Low Rigidity Parts. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Padmanaban, K.P. and Prabhakaran, G., 2008. Dynamic Analysis on Optimal Placement of Fixturing Elements Using Evolutionary Techniques. *International Journal of Production Research*, 46 (15), 4177 – 4214.
- Papastathis, T., Ryll, M., and Ratchev, S., 2007. Rapid Reconfiguration and Part Repositioning with an Intelligent Fixturing System. In: *Proceedings of the 2007 International Manufacturing Science And Engineering Conference*, MSEC2007-31036.
- Papastathis, T.N., 2010. Modelling and Design Methodology for Fully-Active Fixtures.

- Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Papastathis, T.N., *et al.*, 2010. Development of a Reconfigurable Fixture for the Automated Assembly and Disassembly of High Pressure Rotors for Rolls-Royce Aero Engines. *In: Precision Assembly Technologies and Systems*, February. Proceedings of the International Precision Assembly Seminar (IPAS2010), Chamonix, France, 283–289.
- Papastathis, T.N., *et al.*, 2012. Dynamics Model of Active Fixturing Systems for Thin-Walled Parts Under Moving Loads. Accepted for publication in: *International Journal of Advanced Manufacturing Technology*.
- Park, E.J. and Mills, J.K., 2005. Static Shape and Vibration Control of Flexible Payloads With Applications to Robotic Assembly. *IEEE/ASME Transactions on Mechatronics*, 10 (6), 675–687.
- Phuah, H.L., 2005. Part-Fixture Behaviour Prediction Methodology for Fixture Design Verification. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Rai, J.K. and Xirouchakis, P., 2008. Finite Element Method Based Machining Simulation Environment for Analyzing Part Errors Induced During Milling of Thin-Walled Components. *International Journal of Machine Tools & Manufacture*, 48, 629–643.
- Rashid, A. and Nicolescu, C.M., 2006. Active Vibration Control in Palletised Workholding System for Milling. *International Journal of Machine Tools & Manufacture*, 46, 1626–1636.
- Rashid, A. and Nicolescu, C.M., 2008. Design and Implementation of Tuned Viscoelastic Dampers for Vibration Control in Milling. *International Journal of Machine Tools & Manufacture*, 48, 1036–1053.
- Ratchev, S., *et al.*, 2005. An Experimental Investigation of Fixture-Workpiece Contact Behaviour for the Dynamic Simulation of Complex Fixture-Workpiece Systems. *Journal of Materials Processing Technology*, 164-165, 1597–1606.
- Ratchev, S., Phuah, K., and Liu, S., 2007. FEA-Based Methodology for the Prediction of Part-Fixture Behaviour and its Applications. *Journal of Materials Processing Technology*, 191, 260–264.
- Rong, Y., Huang, S.H., and Hou, Z., 2005. *Advanced Computer-Aided Fixture Design*.

- Amsterdam: Elsevier Academic Press.
- Ryll, M., 2010. Towards a Software Framework for Reconfigurable and Adaptive Fixturing Systems. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Ryll, M., Papastathis, T.N., and Ratchev, S., 2008. Towards an Intelligent Fixturing System with Rapid Reconfiguration and Part Positioning. *Journal of Materials Processing Technology*, 201, 198–203.
- Sah, S. and Gao, R.X., 2008. Process Monitoring in Stamping Operations through Tooling Integrated Sensing, *Journal of Manufacturing Systems*, 27, 123–129.
- Shirinzadeh, B., 1995. Flexible and Automated Workholding Systems. *Industrial Robot*, 22 (2), 29–34.
- Shirinzadeh, B., 1996. Strategies for Planning and Implementation of Flexible Fixturing Systems in a Computer Integrated Manufacturing Environment. *Computers in Industry*, 30, 175–183.
- Siva Kumar, K. and Paulraj, G., 2011a. Genetic Algorithm Based Deformation Control and Clamping Force Optimisation of Workpiece Fixture System. *International Journal of Production Research*, 49 (7), 1903–1935.
- Siva Kumar, K. and Paulraj, G., 2011b. Geometric Error Control of Workpiece During Drilling through Optimisation of Fixture Parameter Using a Genetic Algorithm. *International Journal of Production Research* IFirst.
- Sudsang, A., Ponce, J., and Srinivasa, N., 2000. Grasping and In-Hand Manipulation: Geometry and Algorithms. *Algorithmica*, 26, 466–493.
- Tansel, I., Nedbouyan, A., and Trujillo, M., 1995. Design of a Smart Workpiece Holder (SWH) to Extend The Useful Life of Micro-Tools. In: *Proceedings of the IEEE IECON 95, 21st International Conference on Industrial Electronics, Control and Instrumentation*, Vol. 1, 116–120.
- Tao, Z.J., Senthil Kumar, A., and Nee, A.Y.C., 1999a. Automatic Generation of Dynamic Clamping Forces for Machining Fixtures. *International Journal of Production Research*, 37 (12), 2755–2776.
- Tao, Z.J., Senthil Kumar, A., and Nee, A.Y.C., 1999b. A Computational Geometry Approach to Optimum Clamping Synthesis of Machining Fixtures. *International Journal*

- of Production Research*, 37 (15), 3495–3517.
- Tian, Z., X., L., and Z., L., 2009. Robust Fixture Layout Design for Multi-Station Sheet Metal Assembly Processes Using a Genetic Algorithm. *International Journal of Production Research*, 47 (21), 6159–6176.
- Tol, U.A., Design of a Mechanically Adaptable Locating and Supporting System for an Intelligent Fixture. Master's thesis, University of Florida, Gainesville, Florida, 2003. .
- Trappey, J.C. and Liu, C.R., 1990. A Literature Survey of Fixture Design Automation. *International Journal of Advanced Manufacturing Technology*, 5, 240–255.
- Tuffentsammer, K., 1981. Automatic Loading of Machining Systems and Automatic Clamping of Workpieces. *Annals of the CIRP*, 30 (2), 553–558.
- Varadarajan, K.M. and Culpepper, M.L., 2007. A Dual-Purpose Positioner-Fixture for Precision Six-Axis Positioning and Precision Fixturing Part I. Modeling And Design. *Precision Engineering*, 31, 276–286.
- Velišek, K., Košťál, P., and Zvolenský, R., 2008. Clamping Fixtures for Intelligent Cell Manufacturing. In: C. Xiong, H. Liu and Y. Huang Y. Xiong, eds. *Intelligent Robotics and Applications*, Vol. 5315/2008 of *Lecture Notes in Computer Science* Berlin Heidelberg: Springer-Verlag, 966–972.
- Vishnupriyan, S., Majumder, M.C., and Ramachandran, K.P., 2011. Optimal Fixture Parameters Considering Locator Errors. *International Journal of Production Research* IFirst.
- Wagner, R., *et al.*, 1995. Fixturing Faceted Parts with Seven Modular Struts. In: 1995 *IEEE International Symposium on Assembly and Task Planning*, 133–139.
- Walczyk, D.F. and Longtin, R.S., 2000. Fixturing of Compliant Parts Using a Matrix of Reconfigurable Pins. *Transactions of the ASME – Journal of Manufacturing Science and Engineering*, 122, 766–772.
- Wallack, A.S. and Canny, J.F., 1994. Planning for Modular and Hybrid Fixtures. In: 1994 *IEEE International Conference on Robotics and Automation*.
- Wang, H., *et al.*, 2010. Computer Aided Fixture Design: Recent Research and Trends. *Computer-Aided Design*, 42, 1085–1094.
- Wang, Y., 2004. A Methodology of Fixture Evaluation, Analysis and Optimisation. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufac-

- turing Engineering, Nottingham.
- Wang, Y.F., Fuh, J.Y.H., and Wong, Y.S., 1997. A Model-Based Online Control of Optimal Fixturing Process. *In: Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, Albuquerque, New Mexico, 2019–2024.
- Wang, Y.F., Wong, Y.S., and Fuh, J.Y.H., 1999. Off-Line Modelling and Planning of Optimal Clamping Forces for an Intelligent Fixturing System. *International Journal of Machine Tools & Manufacture*, 39, 253–271.
- Wiens, G.J., Rao, K.J., and Rippere, T.B., 2010. Active Fixturing for Micro/Mesoscale Machine Tool Systems. Patent [WO 2010/042502 A2].
- Yamaguchi, T., Furushiro, N., and Higuchi, M., 2010. Application of the Active Flexible Fixture to a Peg-in-hole Task. *In: K. Shirase and S. Aoyagi, eds. Service Robotics and Mechatronics: Selected Papers of the International Conference on Machine Automation ICMA2008*. London: Springer-Verlag, chap. 3, 49–54.
- Yeh, J.H. and Liou, F.W., 1999. Contact Condition Modelling for Machining Fixture Setup Processes. *International Journal of Machine Tools & Manufacture*, 39, 787–803.
- Yeung, K.Y., 2010. Fixture Layout Optimisation Based on Genetic Algorithm. Thesis (PhD). University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering, Nottingham.
- Zhang, D., *et al.*, 2006. Investigation of a 3-DOF Micro-Positioning Table for Surface Grinding. *International Journal of Mechanical Sciences*, 48, 1401–1408.
- Zhang, J., Yang, J., and Li, B., 2009a. Development of a Reconfigurable Welding Fixture System for Automotive Body. *In: J.S. Dai, M. Zoppi and X. Kong, eds. Proceedings of the ASME/IFTOMM International Conference on Reconfigurable Mechanisms and Robots*, London, 736–742.
- Zhang, X.M., Zhu, L.M., and Ding, H., 2009b. Matrix Perturbation Method for Predicting Dynamic Modal Shapes of the Workpiece in High-Speed Machining. *Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture*, 144, 177–183.
- Zhang, Y. and Sims, N.D., 2005. Milling Workpiece Chatter Avoidance Using Piezoelectric Active Damping: A Feasibility Study. *Smart Materials and Structures*, 24, N65–N70.

Zhong, Z.W. and Yang, H.B., 2004. Development of a Vibration Device for Grinding with Microvibration. *Materials and Manufacturing Processes*, 19 (6), 1121–1132.