Global referencing systems and their contribution to a versatile production

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***Abstract*—Cooperating systems like robots are an enabler of versatile production. Their integration into production is supported by virtual planning tools today, that are commonly known to provide versatility. Though the alignment of virtuality and production reality is still challenging. The transformation of virtual versatility on the real production cell is the key to allow what is called versatile production. Production research focuses on self-referencing systems, which use global referencing systems (GRS) as a part of the underlying infrastructure to synchronize virtuality and reality. By implementing global referencing systems, production itself becomes the focus of metrology and self-organizes around the planned process autonomously. In this contribution Nikon Metrology iGPS serves as a base for the global referencing system and the self-referencing is enabled using a simple control strategy.**

***Keywords* — Automation; Flexibility; Metrology; Versatile production; Referencing systems**

I. INTRODUCTION

Modular concepts of today's production systems introduce a high amount of planning and complexity in volatile environments. In contrast to specialized automation systems robots may be used to adjust the processes more rapidly [1]. Investing in flexibility strongly relies on predictable market conditions to meet the tradeoff for efficient production in volatile markets. In contrast versatility provides the benefit to work stable at different market levels with lower flexibility demands compared to being purely flexible and require fast-reacting and foresighted acting [2, 3]. The reduction of discrepancies between the virtual planning and the real world production line is the key to versatile production. The use of self-organization as an explanation model leads to the vital role of metrology through the context of global referencing systems. The focus of metrology will shift from the work-piece to the production system during the implementation of global referencing systems.

II. GLOBAL REFERENCING SYSTEMS AS AN INTEGRAL PART OF PRODUCTION ENVIRONMENTS

Production systems demand new capabilities such as reusability, scalability, flexibility or reconfigurability to meet current industry demands [4]. Of particular interest in recent years have been cooperating robots in automated production systems especially in applications with complex assembly tasks and for handling large, heavy or flexible objects [5]. Accuracy is only partly addressed in the research field as it tends to focus on the development of local sensors. The problem of achieving absolute accuracy in the positioning and movement of cooperating robots is addressed at WZL using global referencing systems (GRS) for calibration and control. GRS are metrology enabled workspaces, that are capable of providing common coordinates for the components inside the volume. The concept of GRS assigns the metrology to be a part of the infrastructure independently of the production machines and being accessible as a service for every component of the production system. Therefore it is possible to use different measurement systems to form a GRS with scalable uncertainties at distinct points.

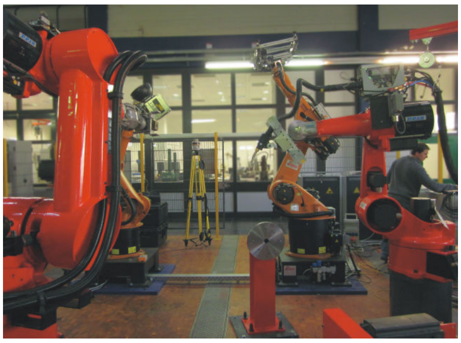

Figure 1: iGPS based robot park at WZL

The functionality and performance of GRS are evaluated in a robot park (Fig. 1) at the Laboratory for Machine Tools and Production Engineering WZL of the RWTH Aachen University. Nikon Metrology iGPS receivers are attached to the robot end-effectors to provide spatial information on the robot poses in six degrees-of-freedom. The kinematics and error budget predict accuracy achievable for the robots to be at least within 0.3 mm for measurements at a rate of up to 40 measurements per seconds [6]. Research and refinements aim at an overall accuracy for robots to be within 0.2 mm to allow their use in nearly all robot applications. A combination of a Kuka KR 60 and a KR16 with a focus on assembly processes is currently extended by a Reis RV130-60 and a RV20-15 to provide the possibility for fixtureless welding. A Fanuc M-1iA/0.5S R-30iA will serve temporarily to integrate GRS-control to Fanuc robots in order to use them for stringer positioning on integral FRP structures. Control strategies with GRS will ensure cooperative operation of robots even from different manufacturers rather than pure multiple robot solutions with hard-wiring.

Calibration and control strategies are engineered to directly execute virtual offline programs without manual teaching needs. The planning tools have become very complex, however lack the feedback from the real world to adjust their internal models. Instead of implementing fuzzy elements for planning conformity, shifting the focus to develop conforming real world elements is another option. A promising approach to allow the stabilization of a system around a working point is known in the system theory as self-organization.

III. SELF-ORGANIZING PRODUCTION SYSTEMS

The emergent behavior of a self-organizing system shows good characteristics concerning scaling and robustness in relation to influences of noise or changes of parameters. Self-organizing systems are suitable as paradigm for complex technical systems. However there are no simple algorithms to produce local rules for the planning of global behaviors. Development approaches are mainly expert-based and expect a fundamental system understanding. Alternatively existing systems in nature are copied, which presupposes however the presence of a suitable example, e. g. the use of ripple marks effect of dunes to influence layer growth of silicon chips [7].

The use of self-organizing approaches may lead to more stable systems in changing environments with multiple interacting entities. First approaches to use self-organization were developed [8] and established highly adaptive systems. The concept of self-organization is only partly addressed in manufacturing science [9]. Successful approaches to deal with self-organization in management science [10] switch the technical to the social perspective of strongly interacting systems. The main criteria to describe self-organization are redundancy, autonomy, complexity and self-reference [11].

In self-organizing systems no separation between organizing, arranging or steering parts takes place. All parts of the system represent potential actors and impose a high degree of redundancy. The relations and interactions, which define the system as unit, are determined only by the systems itself. This autonomy only refers to certain criteria, since a material and energetic exchange relationship with the environment still exists. Systems are complex, if their parts are interlaced by mutual, permanently changing relations. The parts can change likewise at any time. Complexity makes it more difficult to describe or foresee the behavior of systems completely. It may be defined, from a metrology point of view, by the amount of sensors needed to describe system behavior. Self-referencing exhibits an operational closeness. That is, 'each behavior of the system retroacts on itself and becomes the starting point for further behavior' [11]. The use of a global referencing system provides the capability for the production machine to self-reference because of aligned and synchronized coordinates in both virtual planning and the real world. Operational closeness acts not due to external environmental influences, but independently and solely responsible out of itself. Self-reference represents however no contradiction in relation to the openness of systems [11] and represents the metrological part of self-organization by needing a global referencing system.

The basic mechanism of self-organization is the exploration of different regions in the state space until an attractor is reached, a configuration that closes in on itself. This exploration may be performed by deterministic or stochastic variations of the dynamic system. Therefore self-organization depends strongly on noise in the system and may be accelerated or deepened by imposing more noise [12]. Production processes generally contain a significant amount of noise to support the exploration [13]. In the surrounding of an attractor further variation outside the attractor is precluded, and thus freedom of the system components is restricted to behave independently. This is equivalent to the increase of coherence, or decrease of statistical entropy, that defines self-organization [12]. The most challenging application of a complex socio-economic system that relies on self-organization, rather than centralized planning and control, may also be adapted to the technological systems of production.

Future developments in the science of self-organization are likely to focus on more complex computer simulations and mathematical methods. However, the basic mechanisms underlying self-organization in nature are still far from clear, and the different approaches need to be better integrated [12]. In production environments the planning approach in the virtual world is widely used and a formal definition of fitness for various formally defined systems by computer simulation is already carried out. The validation of the models used for this kind of simulations however currently lacks focus and may be performed by using global referencing systems. Types of variations, fitness functions and attractor dynamics of common natural systems (physical, biological or social), are only partly understood and are needed to be extended to technological points of view [12]. Knowledge processing and the ability to choose those models, out of the infinite number of possible mathematical models or black box modeling, may be eased by using a systematic model like the management of measuring processes, that is putting a strong focus on the validation and reliability of data [14].

A. Suitability of measurement systems for use in GRS

Global referencing systems may be used as the tool to provide the data for integration of metrological attractors. They provide numerous alternatives for measuring pose accuracy in complete production environments, such as the use of laser trackers, digital photogrammetry and multilateration [15]. Research on sensor integration and sensor fusion has overcome many of the limitations of vision systems [16]. However, neither completely satisfies the need for both absolute accuracy (pose errors) and dynamic accuracy (path errors) as well as robustness and multiple point capabilities. They may serve, however, as a part of a global referencing system to raise the quality of data in certain regions or for special tasks. The iGPS system of Nikon Metrology provides both static and dynamic six degree-of-freedom (6DOF) pose measurements of robots (for e.g. calibration and control) within large measurement volumes [17] and may serve as a system to provide a basic global referencing system.

The difficulty with assessing the accuracy of the iGPS metrology system for the use as a global referencing system is the dependence on the configuration [6]. A preliminary error budget considers error sources and propagation of errors especially for linear, angular, process and environmental errors. Further sources of error exist that affect the system performance (e. g. shot noise from sunlight, temperature fluctuations and vibrations, reflections of the laser beams result in signal distortions and multi-path errors). The iGPS system is limited by the sampling rate of 40 Hz, which is suitable for static readings; the accuracy of the position measurements of sensors in motion is reduced. Additionally, as stated by Maisano [18], the sampling rate of each transmitter depends directly on the unique angular speed of its rotating head. As such, the sampling rates of each transmitter are different and thus it is impossible to receive concurrent data from all the transmitters. This results in location errors and reduced accuracy for real-time kinematic measurements, particularly for rapid motions. The position results generated for kinematic measurements are also delayed, which will result in instability of the robots when used for feedback control [19], meaning either Kalman filtering or the inclusion of other local measurement systems will be necessary for control applications as latency in feedback control limits gain factors and reduces system dynamics [20].

B. *Self-referencing positioning and path following*

The engineering approaches to compensate path deviation are controlling and calibration and have been explained using iGPS for physical path correction [21] and adjustment of measurement results [22]. The self-organization approach generally tries to use more simple rules to compensate behavior identified as not being conformant by the production system itself. This approach strongly relies on using a global referencing system to ease the surveying of programmed and achieved movement in an aligned and synchronized coordinate system. A full calibration procedure performed parallel to the production process, without interrupting it, would called self-referencing. A simple software option on the robot controllers to adjust programs (automated teaching) also allows self-referencing behavior.

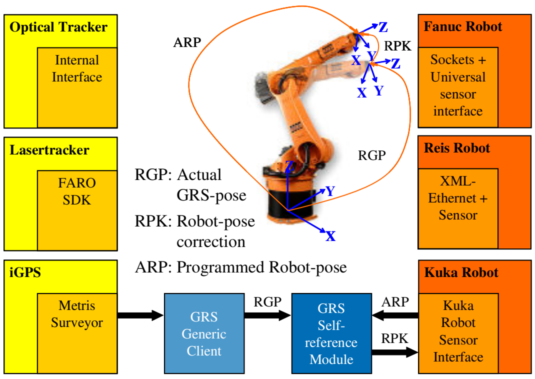

Figure 2: Current self-referencing control strategy at WZL

Control feedback allows self-reference and is shown as the application scenario in this contribution. By directly overlaying the deviation between the programmed path (ARP) and GRS data of the robot movement (RGP) closes in on itself (Fig. 2). The symbols used to calculate the correction value (RPK) represent internally synchronized relations (time, geometry) of the robot and GRS (eq. 1):

$$RPK = (RGP)^{-1} ARP \qquad (1)$$

The GRS-approach works independently of the measurement system. Although the procedures in this example scenario were carried out by using iGPS as the only element of a measurement system, the control strategy does not rely solely on iGPS. The generic client of the GRS may be exchanged by other clients to support or feature lasertrackers, camera systems or a measurement arm currently developed at WZL. The task of the generic clients is the access and transformation of data from the measurement coordinate frame in the GRS frame and to provide the information through a unified object accessible by every component of the production system.

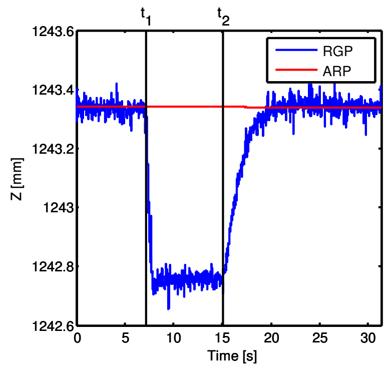

Figure 3: Self-referencing positioning during handling process

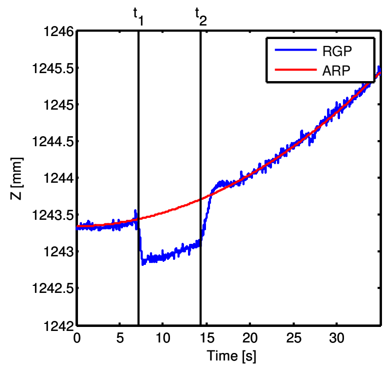

Figure 4: Self-referencing movement during handling process

The effect of using self-referencing control strategies are visible in a simple robot task (Fig. 3,4). The robot starts fully referenced and disables the self-referencing module just before adding a large work-piece on the gripper. The robots bends down, which is immediately visible in the GRS. After a short period self-reference is enabled again and the robot immediately starts to correct the position. This is classical control behavior, however the same procedure is fully independent from the measurement systems itself. A self-referencing module uses the GRS instead of a single measurement system to adjust the behavior. Self-reference also allows the control during movements. The limitations of the underlying measurement system directly influence the self-referencing behavior. Especially for iGPS as the data provider in this example, dynamic processes still impose deficiencies and are a strong research focus at institutions around the world. Tests at different configuration and gain factors show stable control up to about 100 mm/s or 5 % of the nominal path velocity. However this example just uses iGPS in the base configuration and may be easily extended by e.g. a lasertracker to raise the spatio-temporal working range.

IV. Conclusions

In the system theory the stabilization at distinct working points is described by self-organization. The concept is currently used mainly in natural and socio-economical sciences however may easily be extended to the technological production systems. The metrological criteria of self-organization place metrological attractors on the virtual planning points to synchronize the real production systems. The approach relies on simple rules and the capability for the systems to evaluate their own behavior with data from a global referencing system. Metrology is a key factor for high wage countries to regain production capacities in volatile markets by transferring versatility into versatile production.

Self-organization as a mean to transfer versatility into the real production will lead to an ease of planning for highly complex production systems and will create autonomous and redundant production concepts. Scenarios for the self-referencing approach using GRS are investigated in an expert group in the following topics:

- Automated joining of body sections of small business jets with a combination of iGPS, laserradar and an optical coordinate measurement system
- Joining of Fuselage structures of large passenger aircraft to lower the requirements and rework efforts on fixture placements
- Tape-Layup of CRP-aircraft structures with autonomous robot platforms with the integration of a classical machine controls
- Assembly of truck axles with self-driving transportation vehicles and documentation of safety-related screwing processes
- Reuse of production lines in the automobile industry by exchanging hard-automation with robots and establishing a production process driven design
- Automated solar panel manufacturing to shorten setting-in time during construction to lower space requirements and a raise of capacity flexibility

In combination with a global reference system to evaluate the geometric behavior robots or any other entities of a production system are able to be self-referencing. The virtual planning may be adopted directly on a self-referencing system and even cooperative applications are possible. Generic clients for global reference systems are a prerequisite for self-reference. The gaps between different production systems and the gap between the virtual and the real world will be reduced by aligning and synchronizing them in a common, global coordinate system.

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