Concept of a Virtual Metrology Frame Based on Absolute Interferometry for Multi Robotic Assembly

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Abstract. Highly individualized and customized products with dynamic lifecycles increase the need for flexible and reconfigurable assembly systems. Industrial robots are a key technology for future production systems especially for large scale components. The trade off between increasing work piece dimensions and constant or even increasing tolerance requirements, that are in some cases comparable to micro assembly systems, has to be solved by flexible and precise manufacturing and fixtureless assembly processes.

Keywords: Multi Line, virtual metrology frame, assembly

1 Assembly of large scale parts

The achievable accuracy of a robot based assembly system is influenced by the weight of work pieces and end-effectors, process forces, gravitation and temperature of the surroundings. Manufacturing, handling and assembly processes of large scale parts often take place in production sites with harsh environmental conditions. Temperature changes are influencing the handling kinematics as well as the work piece geometry.[1] The deflections lead to inaccuracies during the handling and assembly process that complicate the compliance with the required tolerances.[2]
A process integrated frequent calibration of the robot kinematic can help to improve the positioning accuracy of the robot. The calibration routine should be quick and repeatable. For a number of kinematics within the same working area a calibration with a calibrated material standard is possible. The material standard displays the same manufacturing and assembly tasks as the later product. Therefore the manufacturing of the standard is time consuming and the method is inflexible and expensive especially for large scale parts. Other methods aim to improve the positioning accuracy of the robot kinematics by the use of Global Reference Systems (GRS). The GRS defines a communication network for the exchange of information such as the position of manipulating machinery and non-manipulating devices of a production system. For manipulating machinery, large-volume measurement systems [3,4] such as indoor-GPS (iGPS) and laser trackers are suitable [5,6,7]. For non-manipulating devices, deviations are detected by local sensors e.g. machine-vision systems, light-section

adfa, p. 1, 2011.

or force/ torque sensors. They are capable of measuring local features and require additional data from other GRS- integrated systems. This information is necessary to transform the 3D CAD data into the reference system and aligned the real work piece to final geometry. The integration of the measurement technologies is expensive and the measurement uncertainty is approximated >100µm without the influence of very harsh environmental conditions. That does not meet the accuracy requirements of many assembly processes.

2 New measurement technologies for maximum precision

Etalon´s Absolute Multi Line is a new measurement system based on frequency scanning interferometry (FSI) and seems to be capable for a reconfigurable, fast and very precise calibration of a number of robot kinematics in the same working space. The measurement system is able to measure 24 absolute lengths with an uncertainty of U=0,5+0,5µm/m (interferometry uncertainty). The set up consists of 24 optical fibers and a reflector mounted on the Tool Center Point (TCP) of the robot. The laser lines can easily be integrated along typical working paths of the robot. For the calibration the robot will move the reflector into the beam and run a calibration sequence along the laser beam. At each point the measured length between the end of the fiber and the reflector will be compared to the length calculated from the positioning information of the robot. The deviations between the data can be used for an evaluation of the robot´s positioning accuracy and be compared to the accuracy required by the holistic tolerance management. In addition the information shall be used for an online compensation of the robot path. But there is an even more sophisticating solution to enable an online calibration and even control of the robot kinematics. This approach requires the ability to track a target which is mounted on the robot´s TCP by multiple interferometry distance measurements. Therefor the system need the ability to track a target mounted on the TCP of the robot. The mechanical concept is presented in this paper.

3 Virtual metrology frame

In the 1960's Brown described the idea of a "virtual metrology frame". Greenleaf illustrated the principle of a selfcalibrating surface measuring machine in 1983 as shown in figure 1.

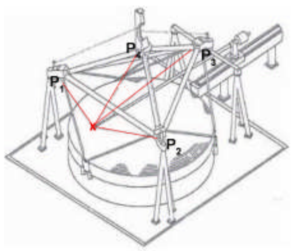

Figure 1: Selfcalibrating surface measuring machine

The concept is based on the multilateration principle. The fundamental elements of a measuring system based on multilateration are laser-interferometer-based tracking stations, retro reflectors and a mathematical approach to determine the spatial coordinates of the measured points. The “virtual metrology frame” of the present approach is based on the “High-Accuracy CMM” presented in 2000 by Hughes (National Physical Laboratory, UK). The position of the TCP equipped with retro reflecting targets is tracked and measured by fixed measuring stations located at appropriate positions around the working zone of the robot kinematics. As Hughes points out the virtual metrology frame approach will use eight measuring stations or better eight “lines of sight” to achieve a six degree-of-freedom measurement capability.[Design of a High accuracy CMM]

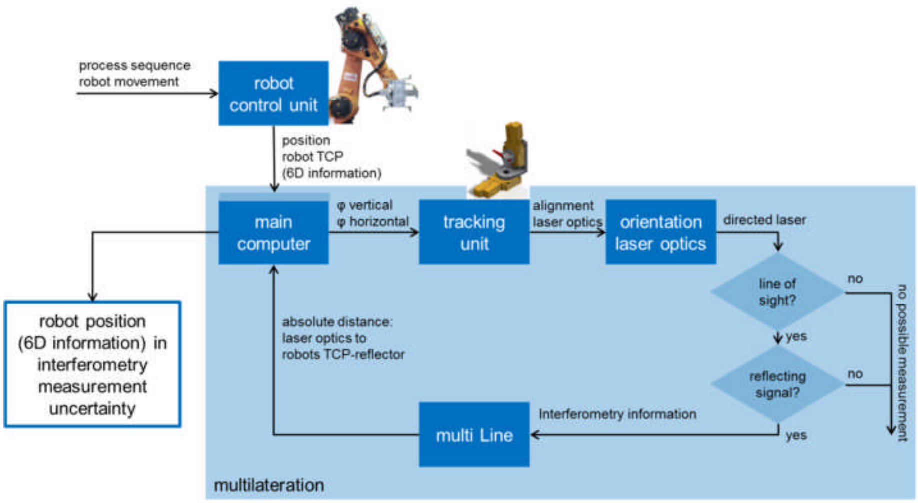

Figure 2: Description of the tracking system for multilateration

Figure 2 describes the concept for tracking the reflecting elements in detail. The tracking of the targets is based on the operational control data of the robots. The 6D information for position and orientation of the robot´s TCP is sent to the main computer of the multilateral measurement system. Due to the known position of the robot and the tracking units the main computer calculates the vertical and horizontal angle for each rotating stage of the tracking units to align the laser optics with the appropriate reflector which is attached to the robot´s TCP. The aligned laser optics emit the directed laser beam. If there is a line of sight and the reflected signals quality is adequate the interferometry information arrives in the Multi Line. The Multi Line determines the absolute distance between the laser optics and the robot´s TCP- reflector. Information about multiple distances are necessary to use multilateration for calculating the robot´s TCP position. The result is the robot´s TCP position (3D information) in interferometry measurement uncertainty.
The challenges regarding the line of sight and the reflecting signal quality will be addressed in chapter 6 “Boundary conditions for absolute interferometry in multi robotic assembly”

This system uses multiple tracking units, which consist of to rotatory stages, to track multiple reflectors. As described the position of the robot´s TCP is known from the robot control unit (figure 2). Each tracking unit can be designed to a more favorable price because the tracking is based on known geometric information and not on complex and active tracking area sensor (in particular PSD). Compared to the laser tracer (each unit has got an own interferometer and a complex active tracking routine) the described concept is using a single multi line system (up to 88 channels) and multiple favorable tracking units which consist of common rotatory stages. By scaling the number of measuring points, this concept is much more favorable than a comparable solution with laser tracers.
An additional advantage because of the absolute interferometry is, that the tracked target can changed by reposition the laser optics with the tracking units to a different robot´s TCP reflector. This allows the control of multiple targets in an assembly cell with a high number of cooperating robots.

4 Test setup and improvement potentials

The test setup consists of 4 robot kinematics, solving cooperating working tasks in the same working space. The TCP of each robot is equipped with a reflector of the measuring system. The laser lines are integrated into the working space. They could be used inside the working space as lines of reference for the robot´s position or movement. The reflector is moved along a laserline to reference the robots TCP position into the coordinate system of the GRS. The information of the absolute interferometry measurement is compared to the position-information of the robot control. Based on the result a compensation routine can be implemented that will compensate the deviation of the absolute positioning. The result is a calibration method that improves the positioning accuracy of the robot kinematics dramatically compared to the accuracies which is reached by the control of multiple robots by Nikon´s iGPS. [2,7]
The tracking unit must provide stable, accurate and continuous changes in the orientation of the laser optics beam in the horizontal and vertical direction. In addition, the pivot point has to be defined as reference point of the optical system. A corresponding prototype of a tracking unit is constructed and assembled out of bought-in components. The objective is to build the kinematics at an affordable price. A detailed description of the development is given in chapter 5.

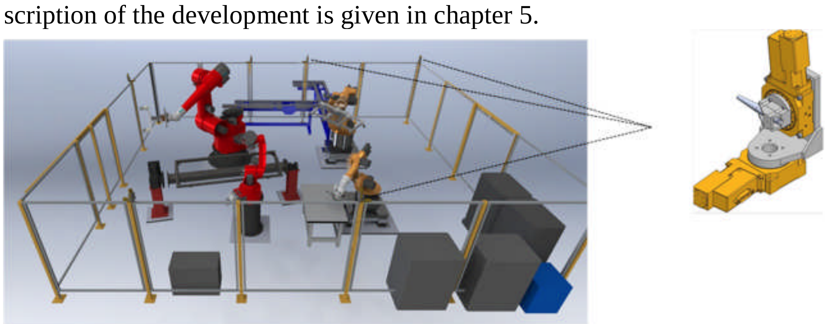

Figure 3: Test setup for multilateration in cooperative robotic assembly

The calibration methods allows the compensation of system deviations in absolute positioning by implementing a measurement system and a calibration routine into the assembly process. The compensation will improve the positioning accuracy of the robot kinematics and the accuracy of the assembly process. A simulation of the work piece deflections will complement this approach for maximum precision in the assembly of large scale parts. [1]

5 Development of the tracking units

To guide the laser optics multiple low price tracking units are necessary. The units must align the collimator to the reflectors, which are attached to the robot´s TCP. The tracking unit´s positioning ability must be accurate enough to hit the reflector area (cateye) with the laser beam over a distance of more than 20 meters.

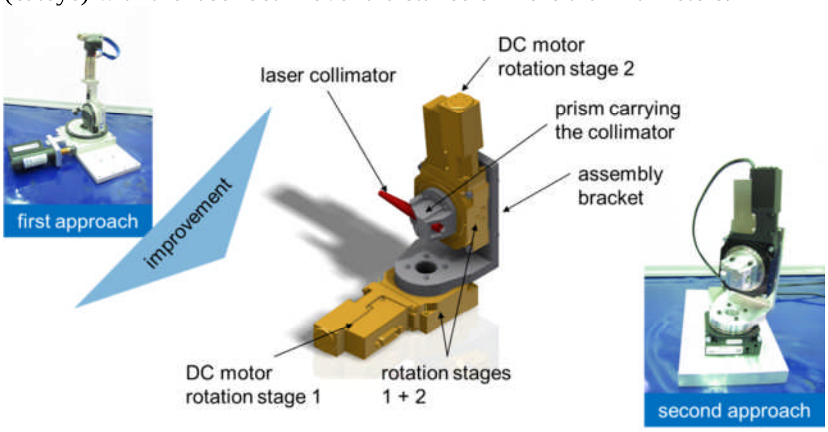

Figure 4: Tracking unit

Figure 4 shows the developed and improved tracking unit, which consists of two rotating stages (URS 50 BCC Newport) with a minimum incremental motion of 0.001° and a guaranteed absolute accuracy of ±0.04° [8]. Both stages are connected by an assembly bracket and the collimator is carried by an prism.

The improved tracking unit is more robust and can carry heavier loads. The uni- and bi- directional repeatability is improved and the wobble error is minimized. Additionally, the following constructional improvements are realized. The laser collimator can be positioned reliably and reputably in the middle of both rotation axes by the use of the prism and a fixture. The cables of the rotation stage and the optical fiber can be routed through the rotation stage and the ground plate to avoid damage. The upper rotation stage is adjustable in height to investigate and minimize the influence the wobble error of the stages.

In the future piezo-electric driven rotary stage or a goniometer could raise the accuracy of the tracking unit if necessary.

6 Boundary conditions for absolute interferometry in multi robotic assembly

Line of sight visibility and a high signal quality of the reflected laser beam are required to take full advantage of the interferometry system´s accuracy. The complexity of assembly processes and the use of multiple robots result in spatial constraints that increase difficulty to fulfill these requirements.

There are strong dependencies between all (moving) elements in the working area. (e.g. work pieces, fixtures, tooling, grippers, safety fences, robots, etc…) All these elements are obstacles and must be taken into account when planning the assembly process. Also the multiple number of reflectors to determine a position and distance information performing multilateration are challenging.

Additionally the tracking units have got moving constraints and the opening of the reflectors (cat eye) are limited to approx. ±30°. All these boundary conditions limit the scope and solution space for positioning the tracking units and providing a direct line of sight to the reflector.

To handle the described challenges and gain all advantages of interferometry measurement a strong simulation of the metrology infrastructure and the assembly process is needed. All boundary conditions like the robot movements, characteristics of the tracking units and reflectors which are attached to the robot´s TCP must be considered.

To perform this task a simulation is needed to cope with all influencing factors and the domination of complex assembly systems. Figure 5 shows such a metrology infrastructure for multi robotic cooperative assembly which allows the optimization of complex systems including the measurement system in an early planning phase.

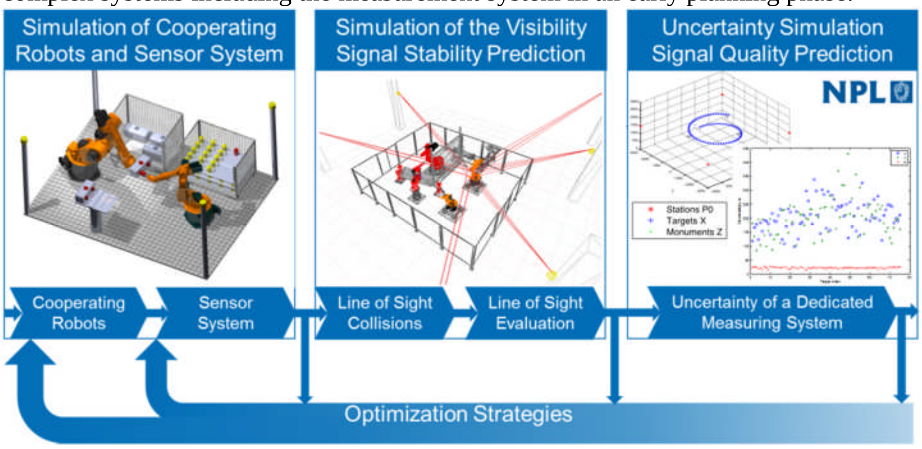

Figure 5: Metrology infrastructure for multi robotic cooperative assembly

The simulation was developed to examine the boundary conditions of Nikon´s iGPS but can be easily adapted to the requirements of the absolute interferometry measurement. This concept includes not only the line of sight evaluation between the sending

and receiving elements but also a model of the measurement systems uncertainty can be implemented to predict the quality of the measurement as well. [9]
The information regarding the line of sight and the predicted measurement uncertainty are used to optimize the assembly system performance for optimum visibility and measurements uncertainty.

7 Optimization strategy for the setup of the assembly process

If the simulation (presented in figure 5) identifies insufficient number of lines of sights to perform the multilateration measurement, setup optimization can be done by repositioning of the tracking units. Therefore the position of each tracking unit is weighted by a criteria and the relevance of the assembly process is considered.

Figure 6: Approach for the assessment for the optimization of the system´s setup

Figure 6 shows the basis approach for the assessment for the optimization of the system´s setup. The first idea is to weight each position of the tracking unit by a criteria. The criteria evaluate the number of line of sights between the tracking unit position and all reflecting elements during a complete assembly process. The positions with a low criteria value must be optimized to a position with higher value of the criteria. (figure 6, left side)
The relevance of the assembly process is illustrated by two welding operations. (figure 6, right side) The robot paths are colored with respect to their relevance for the process. During the robot movement to the start of the work pieces welding seam the relevance is low (green). When the robot is approaching the first welding tip the relevance rises (yellow) and during the welding process the relevance is high (red).
A heuristic approach is moving the lowest rated (with respect to the positions criteria and the process relevance) tracking unit by ± 1m in the X-Y-Z direction inside the simulation. The new position is evaluated and the rating is compared between each position. Comparing the rating of each position shows the next best setup for the tracking units. [10] Both concepts are considered for finding an optimal position for each tracking unit in respect to visibility and process relevance.

8 Conclusion

This paper introduces an approach to integrate an absolute interferometry measurement into multi robotic assembly applications. Brown´s idea of a “virtual metrology frame” and Greenleaf´s principle of a mechanical selfcalibrating surface measuring machine becomes accessible for multi robotic assembly. The 24 Multi-Line channels are positioned and orientated by cost efficient tracking units based on the operational control data and 3D position information of the robots. This enables the tracking of multiple targets by multiple interferometry distance measurements to determine a 3D position information of the robot´s TCP through multilateration. In the future there will be further developments integrating more reflectors to calculate 6D information for the position and orientation of the robot´s TCP.
A strong simulation of the metrology infrastructure incorporates all influences of the multi robotic assembly process and the measuring system. It is possible to optimize the system´s setup in early planning phase to guarantee a strong visibility during the assembly process.
The concept results in a virtual metrology frame which allows to determine 3D position information for multi robotic assembly with the measurement uncertainty of an absolute interferometry measurements system.

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