Self-optimizing Assembly of Laser Systems

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Abstract: Laser assembly can be a tedious task if performed manually. Especially if miniaturization of the laser is desired, robot-based assembly can greatly improve quality, performance and throughput, while self-optimization is regarded as a strategy to reduce planning efforts and increase the robustness of the assembly. An automated laser assembly system has been developed together with a concept to increase the autonomy through a multi-agent system control structure. The multi-agent system allows assembly steps like sequence planning, measurement of components and deviations, selection of components, soldering elements onto a carrier plate and active resonator alignment to be handled by the system itself and enables the assembly system to uniquely plan every laser system and execute its assembly within a flexible robot-based assembly cell.

Keywords: Laser assembly, Self-optimization, Multi-agent systems

1 Introduction

Increasing competitive pressure from countries with advantages in low labor cost demands solutions for modern assembly systems meeting high flexibility and efficiency. The significant differences in input factor costs require a fundamental increase of the degree of automation to enable competitive production in high-wage countries [1]. In addition, automation can be a means to implement 100% reliable processes, to increase quality and to improve working conditions.

However, a high degree of automation often correlates negatively with the flexibility of assembly systems and is the motivation to develop and investigate automated solutions for a highly flexible assembly. The goal is to combine the advantages of automated processes with maximum adaptivity to enable an efficient small or even single batch oriented production of complex products. Complexity results from a wide variety of products, subassemblies and components, demanding flexible assembly systems to keep down-time for setups and changeovers low and increase productivity. Complexity also results from the integration of many different functions into one product, be it the integration of mechanical, electrical and optical functions and components, the combination of different materials, or even the integration of macro, micro and nano components.

It is the goal of this work to demonstrate flexible automated assembly of a hybrid opto-mechanical system consisting of a variety of components with optical, electrical and mechanical properties. Flexibility of the assembly system enables the manufacture of tailored products, while increased planning efforts are reduced through the application of self-optimizing strategies.

2 Automated assembly of the laser

2.1 MicroSlab – a miniaturized solid state laser system

A miniaturized diode-pumped solid-state (DPSS) laser system for marking applications, called MicroSlab, has been designed and developed at Fraunhofer ILT. It features a planar setup and optical components can be easily positioned and assembled on a ceramic carrier plate. Components have a standardized geometry and size to facilitate automated handling and are soldered to the carrier plate. A similarity of design and assembly procedure to surface mounting in electronics (SMD) is explicitly desired and maximizes the flexibility [2] (Fig. 1).

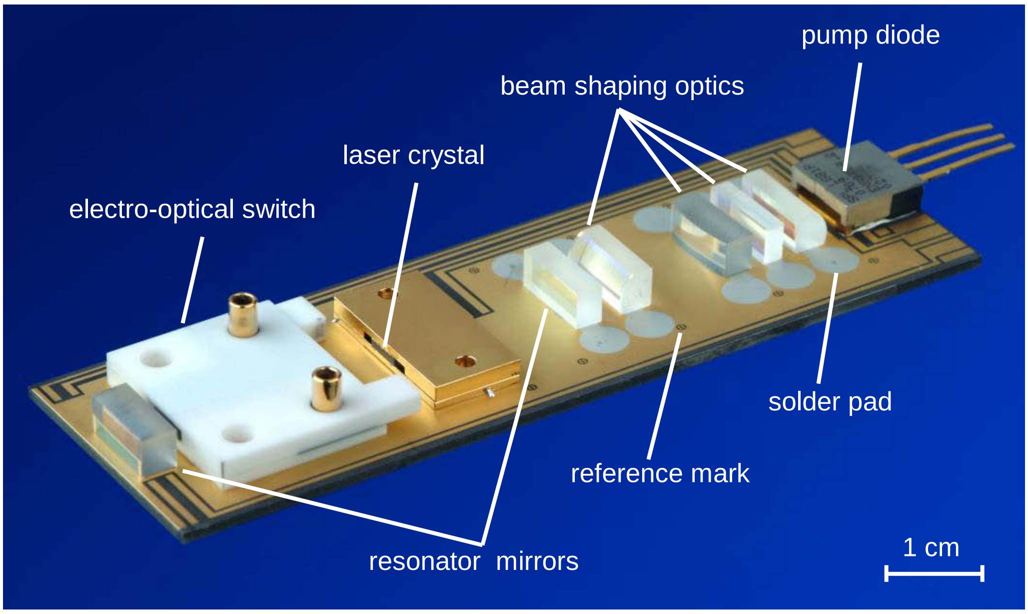

Fig. 1: MicroSlab laser

The laser consists of a pump diode and beam shaping optics as well as a laser crystal and an electro-optical switch enclosed between the resonator mirrors (Fig. 1). The pump diode, a diode laser bar, delivers a rectangular beam of up to 30 W of optical power and is cooled through the surface of the base plate via thermo-electrical elements. The light emitted by the pump diode is shaped to a homogenized line and directed onto the laser crystal by the beam shaping optics. Neodymium doped crystals of slab geometry have been employed as laser active media and the crystal is soldered in a copper housing for better heat dissipation.

In order to achieve high-energy densities suitable for laser marking, short laser pulses are generated with an electro-optical switch, designed and implemented for automated planar assembly. Reference marks on the base plate are used for machine vision assisted positioning. Solder pads are superimposed on the laser base plate for surface mounting of laser components. The table below lists important specifications and typical tolerances for the assembly:

Specifications

average power	5 – 10 W
wavelength	1064 nm
pulse length	10 – 20 ns
repetition rate	DC to 20 kHz

Assembly tolerances

pump line position	20 µm
component position	10 µm
component angles	400 µrad
resonator position	10 µm
resonator angles	35 µrad

2.2 Flexible assembly cell

The vision of future adaptive and self-optimizing production systems pictures subsystems with inherent intelligence – or cognition – communicating and cooperating with each other to achieve subordinate goals. From an IT perspective this can be realized through modular and distributed control systems opening possibilities for future production, employing intelligent system modules which autonomously act on lower hierarchical levels. A fundamental precondition is an entirely modular hardware and software design enabling rapid exchange and fast integration of subsystems. This flexibility combined with a high degree of automation leads the way to adaptive technical systems.

The realization of the underlying technical concept is a multi-robot assembly cell where the described sensor-based assembly operations as well as highly-precise positioning and alignment tasks are being automated (Fig. 2) [2].

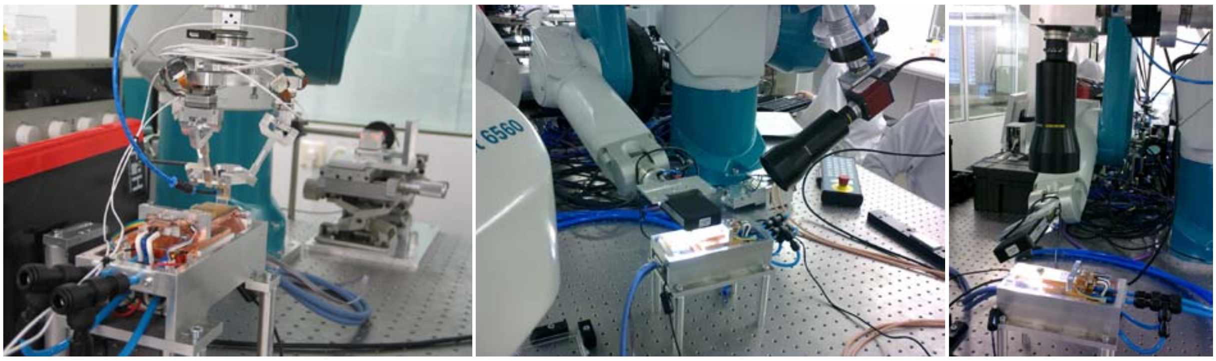

Fig. 2: Flexible multi-robot assembly cell

Central idea of the concept is the realization of a highly modular system architecture through all levels of the assembly system and control, in order to reduce the product individual efforts for configuration and set-up to a minimum. Industrial robots are used to position modular process tools within the assembly area which are used for gripping, alignment, joining or measurement, respectively. For more complex assembly operations, where components are actively aligned and joined directly in position, several tools come into operation simultaneously by means of cooperating robots.

2.3 Assembly steps and processes

Soldering of optical components

To realize automated positioning and joining, a resistance soldering technique for optical components has been developed (Fig. 3). Optical components as well as the ceramic substrate are metalized and a soldering pad is applied to the ceramic carrier plate. During assembly, components are placed on the soldering pad while electric current melts the solder due its high resistance. By using the electrical resistance of the solder itself for selective heat generation in the joining area, optical elements can be successively mounted on the substrate without misaligning already soldered components. In addition, an increase of the electrical resistance at the melting point can be used as a self-controlled mechanism to stop the process [3].

Two similar soldering techniques have been developed, a passive “pick and join” and an active “pick and align” process. Solder layers of the pick and join process are only few µm thick and the joining procedure is fast. However, alignment is limited to three degrees of freedom. For alignment-sensitive optical components, “pick and align” is used. It differs by using a thick solder pad of some hundred µm and permits the optics to be adjusted in all spatial axes while the solder is kept melted.

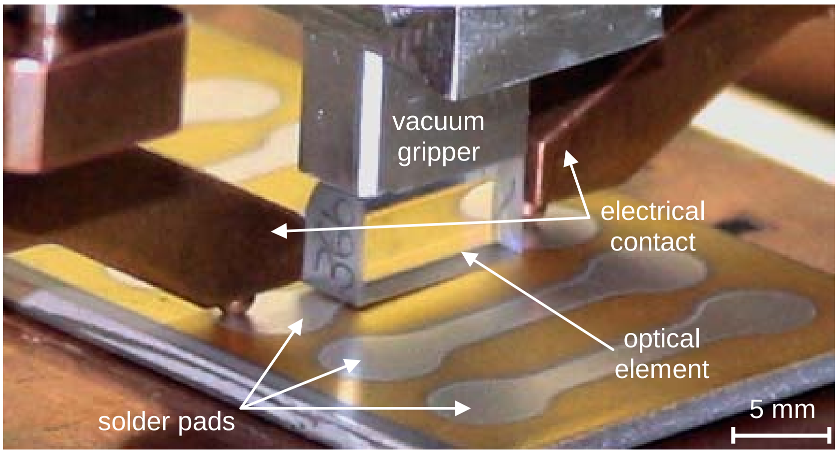

Fig. 3: "Pick and Join" during planar adjusting

Measurement and alignment

The quality of the miniaturized laser system does not only depend on the quality of individual optical components, but also on their accurate positioning and correct pairing. Alignment precision in the range of micrometers is required and component deviations lead to new dynamic reference values for the assembly control loop. Hence, the assembly process should be flexibly designed and supported by adequate measuring systems, capable of assessing its quality state as well as enabling dynamic adjustments of optical components during the assembly.

According to the significance and tolerances of laser specifications, different assembly steps may have to be qualitatively inspected. For a high quality laser system, the following features have to be automatically determined: a) geometric features, b) presence/absence as well as identification of components, c) compliance with positioning tolerances, d) characterization and choice of components, e) active (in-process) adjustment of components with critical positioning tolerances, f) characterization of the laser beam profile as well as its power, g) discovering and solving assembly failure states.

Measuring techniques that are integrated into the robotic cell, in order to assess the assembly state are (Fig. 4): 1) a robot-based high resolution machine vision systems, 2) a camera-based laser beam analysis system, 3) a laser power meter as well as 4) electric sensors for measuring force, temperature and laser current.

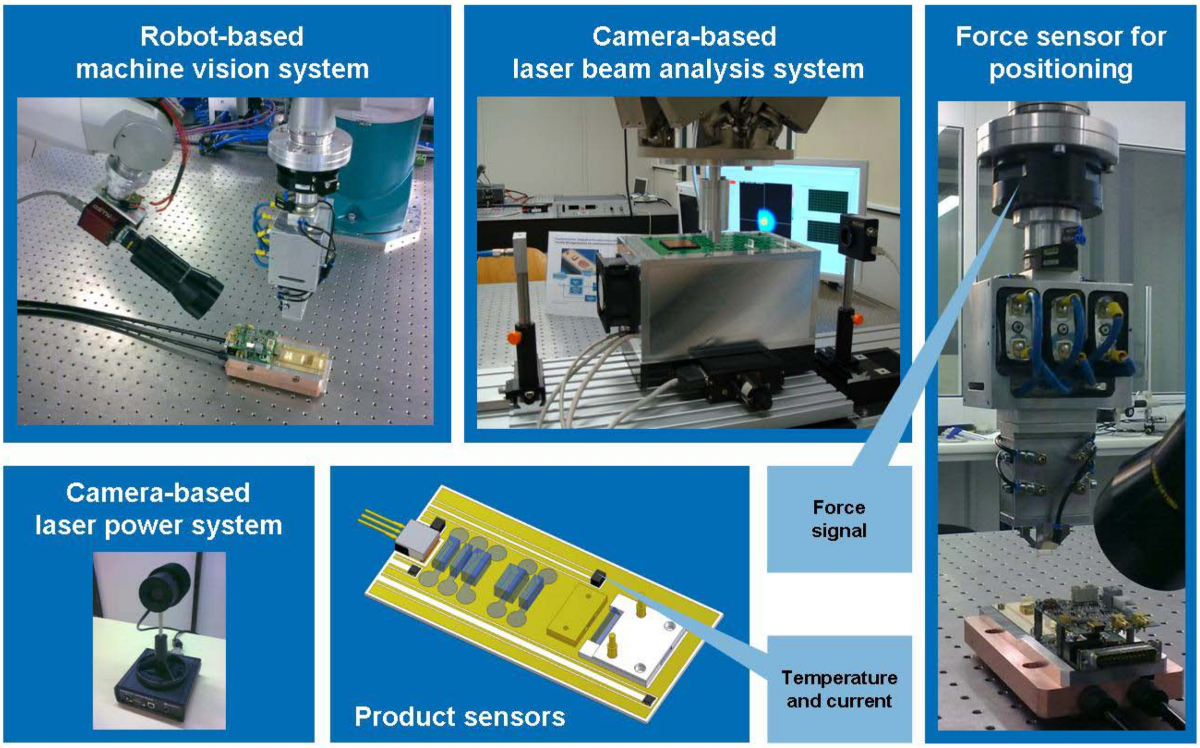

Fig. 4: Measuring techniques used within the robotic assembly cell

Tolerance Matching

Tolerance Matching, a form of selective assembly, is employed to facilitate the adaptation of parameters that cannot be adjusted due to geometrical restrictions. Vertical alignment of optical components is limited due to planar placement restrictions on the base plate. A Tolerance Matching example is the selection of lens components with suitable centrations to compensate deviations of laser crystal and laser diode.

In contrast to selective assembly, Tolerance Matching seeks to match components individually, instead of sorting them into groups that can be selectively assembled. While tolerance classification is useful for mass production, Tolerance Matching makes it possible to create suitable matches even for a small number of available components, if measured characteristics are tracked during component lifetime [2, 4].

Tolerance Matching requires the measurement of component characteristics that have a large influence on product performance after assembly and is integrated into the multi agent sequence planning. Clearly, some component combinations will perform better than others and it is the goal of the Tolerance Matching strategy to select those. With the help of simulations, the best match for a set of components is then found and selected out of all possible combinations. Finding the optimal solution for a set of components avoids the complication of mismatch, which arises during classification due to unequal component numbers in matching tolerance groups and makes use of every component.

Simulations prior to actual measurements and assembly are performed to optimize tolerance specifications and assure good matching capabilities [5]. Simulations of Tolerance Matching used to compensate pump laser beam height are shown in Fig. 5 for a set of five components.

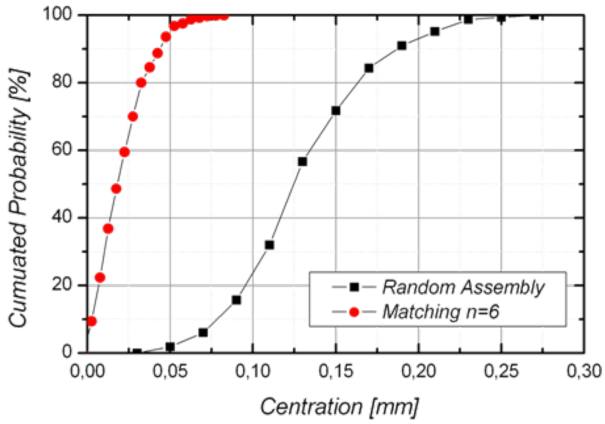

Fig. 5: Simulated Tolerance Matching applied to align laser crystal and pump beam

3 Flexible assembly through self-optimization

Self-optimizing assembly systems strive for high adaptivity, facilitate a significant reduction of planning efforts and enable highly flexible automation. By definition, self-optimizing systems are characterized by the generation of new system objectives based on a continuous supervision of the current system state and adaptation of the system's behavior to these new objectives [6,7]. Self-optimizing production systems are thus considered intelligent systems that can react autonomously and flexibly to their surrounding environmental conditions, external users or systems and also to their own dynamical behavior. These systems are usually able to learn with their own experiences and remember from past events, which may help predicting new events and optimizing their behavior in future situations [6,7].

During automated assembly of a complex and sensitive system, like the MicroSlab laser, unexpected situations occur frequently and would stop the execution of a strict automation procedure. A flexible assembly enabled through self-optimization has the potential to resolve situations that require adaptive assembly processes and results in a robust automated assembly.

3.1 Active resonator alignment

The alignment of the laser resonator is a key step in the fabrication process of a solid state laser. An increased complexity of this task results from high requirements on component positioning which have to be aligned under continuous observation, evaluation and optimization of laser output parameters. Process and component tolerances play an important role as every alignment starts with new and unpredictable conditions, requiring a self-optimizing process approach.

The MicroSlab resonator consists of two mirrors – the incoupling (curvature radius of 500mm) and the outcoupling mirror (plane) – forming a plane-concave resonator. The reflecting surfaces of both mirrors have to be aligned to each other and to the pre-assembled laser crystal with angular tolerances of a few millidegrees. As the effort to characterize and measure these features for all components is unacceptably high, self-optimization of the alignment is a promising approach to reduce planning efforts and increase the efficiency of an automated assembly.

The self-optimizing alignment process has been designed as a two-stage process with:

- A passive alignment of both mirrors by means of a reference laser beam;
- An active alignment, where the laser is being switched on and the functional output of the systems is being measured, evaluated and optimized.

The passive alignment method is based on a low power reference laser pointed to the mirror being aligned, whose reflections are guided in such a way that they are projected on a screen. This setup has been analyzed geometrically and a model describing the relation between the distance of two reflections on the screen and the differences in angular orientation has been found. These relations have been embedded in an alignment algorithm to enable an automated alignment of both mirrors to the reference beam.

As the achievable precision of this process design is still below the required parallelism of the mirrors, an additional active alignment step becomes necessary. Active methods are based on monitoring the behavior of the system during assembly. In accordance with the definition of self-optimization, three steps are executed repetitively until the desired system status has been reached:

1) The current system status is characterized by a certain mirror orientation and a corresponding output power. As the orientation cannot be measured directly, the output power is used as a reference. Therefore, the mirror orientation is changed stepwise – in the direct surrounding of the initial position – while output power is measured. The known output power profile is matched into the resulting point cloud to estimate the initial system state;
2) Based on the first step, the two angles for the estimated maximum output power can be calculated and set as the new system state (objective);

3) The component is rotated according to the new system objectives and the process is restarted with adapted parameters (step width, search grid size) until a certain preset output power (external objective) has been reached.

Based on this self-optimizing approach a significant time reduction for the active alignment could already be achieved and further improvements promise a total alignment duration for the resonator of less than five minutes.

3.2 Automatic assembly sequence planning

Planning an adequate assembly sequence for the automated assembly of a complex product requires the knowledge and anticipation of possible system states, failure modes and ways to resolve problems. Clearly, this is a difficult and time-consuming task to accomplish prior to the assembly and cannot include every conceivable situation that might occur, yet the robustness of the assembly depends on a reliable sequence. Using self-optimization as a tool to enable the assembly system to react to changes and adopt a behavior that leads to satisfactory results is expected to increase the robustness.

An assembly sequence consists of positioning components, measurement and alignment steps as well as possible Tolerance Matching and is expected to result in acceptable performance of the system. For the pump optics, four specifications are critical: the vertical and horizontal positions of the pump line relative to the laser crystal, the width of the line and its horizontal orientation. In order to model the assembly, these specifications are described as functions of component positions, orientation and critical component parameters such as radius of curvature or centration.

With this model, given tolerances and assembly precision, the expected performance of the pump optics can be expressed in terms of the four specifications and is given as a probability. The task of the sequence planning is now to select a sequence of actions that results in a high probability to fulfill all of the four system specifications. Depending on tolerances, robot precision, available measurement equipment or desired performance specification, the optimal sequence will be different. Sometimes it will even be necessary to change specifications or correct input data during the course of the assembly. The dynamic evolution and sheer number of possible sequences demands an intelligent solution to avoid the advance manual evaluation.

With the provided assembly model and a set of rules describing allowable and feasible actions, a self-optimizing sequence planner can determine a suitable sequence based on evaluations of the model. During application of the strategy, dynamic changes can be initiated based on measurements and model predictions.

3.3 Failure states

The identification and interpretation of assembly failure states will be handled in this project through the combination of measurement systems directly supported by an expert system. The main difference of an expert system in comparison to other knowledge-based systems is the source of covered and acquired knowledge, which comes directly from specialists and experts [8].

This failure tolerant system collects a large amount of “if-then” rules among its rule-based knowledge, which together build up a dynamic systematization of the laser assembly. Distinct information about the assembly process is stored in the knowledge base, such as the different components of the system, their placement and positioning tolerances, the metrological systems available for the inspection of the assembly, as well as the other hardware resources needed for the control and adaption of the system state.

In order to provide a preventive and pro-active intervention of the failure tolerant system during the assembly procedure, planning information must be exchanged with other modules of the assembly system, so that the different rules of the knowledge base can be triggered at the correct time, according to the current and future planned state of the assembly [9]. Initially, failure states of the assembly have to be identified (clear divergence between the desired and current condition of the system) by the acquisition and analysis of metrological data. This process flows under control of the rule-based knowledge of the system and results in the logic diagnose of the system situation. In the sequence, the causes of the detected failures must be detected and interpreted. In some cases the application of extra metrological inspection can help finding these causes and deriving adequate measures to act back on the system to correct those failures. The process of correlating a failure with an adequate solution is usually supported by past experiences contained in the case-based knowledge of the system. Fig. 6 illustrates a typical failure state during the beginning of the assembly of the laser system.

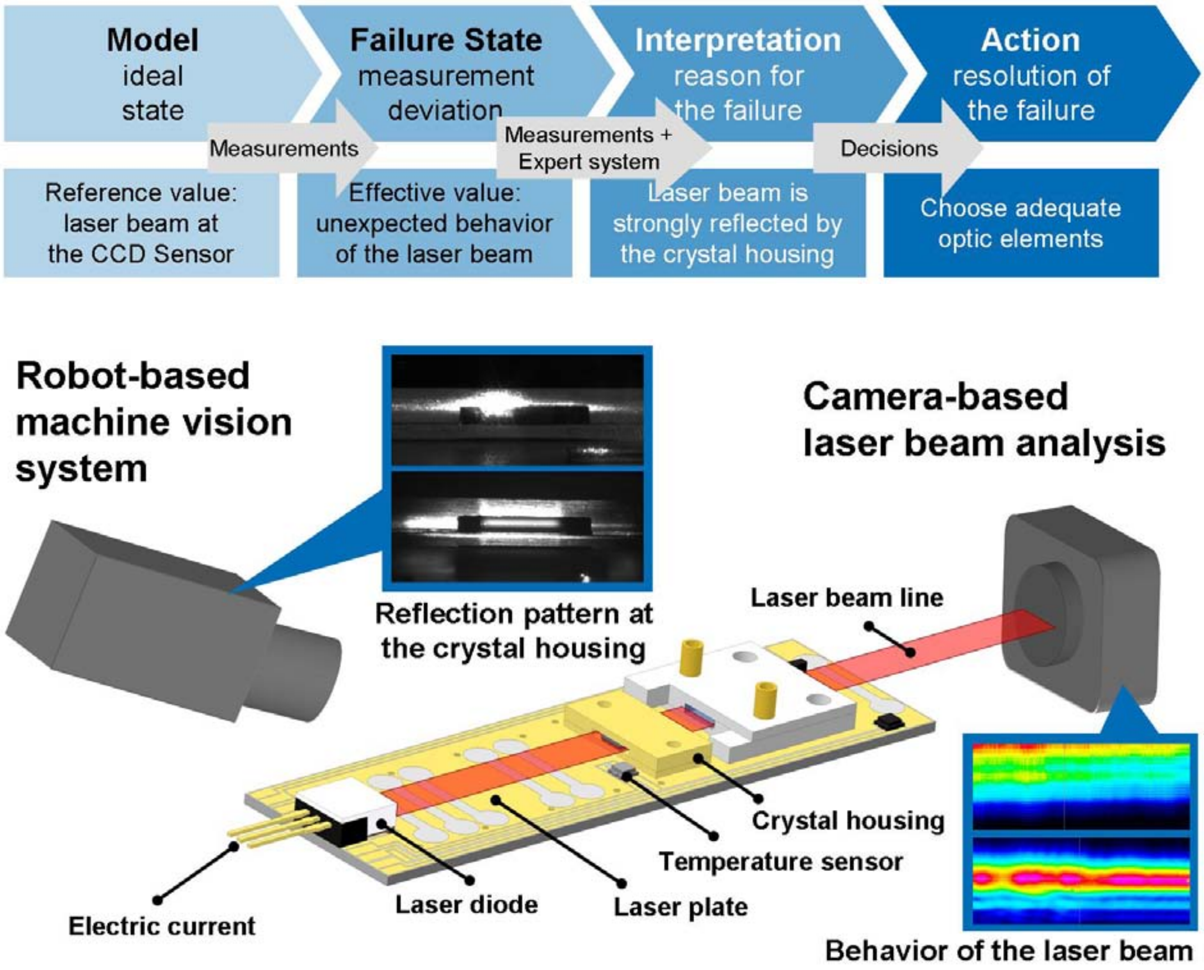

Fig. 6: Systematic procedure and example for identifying and handling assembly failures

In this example, the laser beam that is ideally centered on the laser crystal is off center and hits a portion of the crystal housing. The failure is usually detected during laser beam analysis by perceiving that the laser beam line features a strange and unexpected behavior. The causes of such a failure can be confirmed by inspecting the crystal housing's frontal surface, showing a strong reflection pattern. As laser diode and laser crystal and its housing are already firmly fixed onto the laser plate during detection, there is no way to correct their position to try to improve the initial conditions of the assembly. One possible solution in this situation is to dynamically choose the optical components of the beam shaping optics and change their assembly sequence. In order to perform this new planning task, the current state of the assembly (positioning and tolerances of the laser diode and crystal) must be assessed and constitutes a new internal goal.

4 Multi-agent system approach

Multi-agent systems (MAS) have been identified by many experts as a key factor for improving flexibility and autonomy in different branches of the automation engineering. For manufacturing and assembly, agents can bring an innovative control approach by distributing and sharing responsibility for the accomplishment of different production tasks.

The modeling of the control of a flexible laser assembly system with an agent-based approach strives for an autonomous and optimal use of production resources, as well as for a reduction in time and complexity along the production chain [10,11]. Benefits of multi-agent systems for the assembly system are, among others: easy introduction of new agents (software/hardware), use and interaction of different operating systems and programming languages as well as an extended autonomy [12].

4.1 Development of a multi-agent system

Literature agrees that "an agent is an entity that perceives its environment through sensors and can provide it feedback through actuators" [10]. The agent autonomously follows one or more goals and is usually in close contact with other agents in order to accomplish these goals. Before the agent itself decides how to behave or proceed to perform an action, it takes different factors, such as own goals, knowledge, cumulated experience or perception into consideration (Fig. 7).

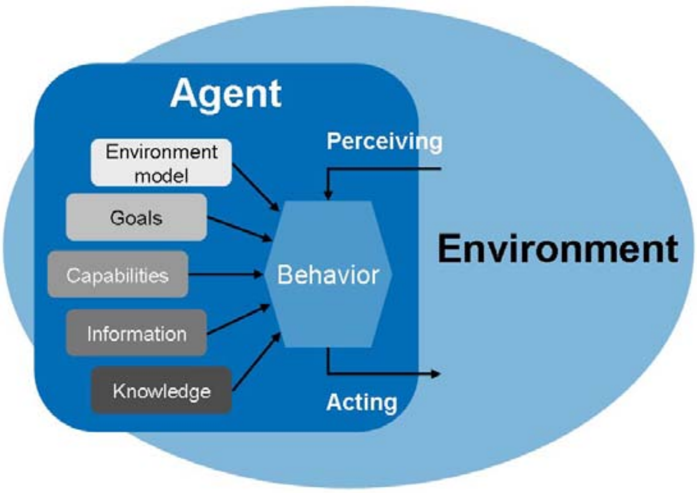

Fig. 7: Model of a software agent

The development of software agents focuses on the decomposition of a problem and distribution of responsibility among smaller and autonomous entities, which follow specific principles to achieve their local and global activities. These can be encapsulation, goal orientation, reactivity, autonomy, pro-activity, interaction, persistence, adaptivity and intelligence or learning skill [11,13].

Inside a multi-agent system, agents differ according to their capabilities and degree of responsibility. From a functional point of view, there is no specific commandership hierarchy among the agents. From an organizational perspective though, the modeling and conception of an agent-based structure following a specific agents' hierarchy can be helpful in terms of understanding the system, as the hierarchy highlights the difficulty implementation level and functional importance of different agents. Fig. 8 illustrates the complete agent-based structure of the assembly control hierarchically organized in distinct operational levels [12].

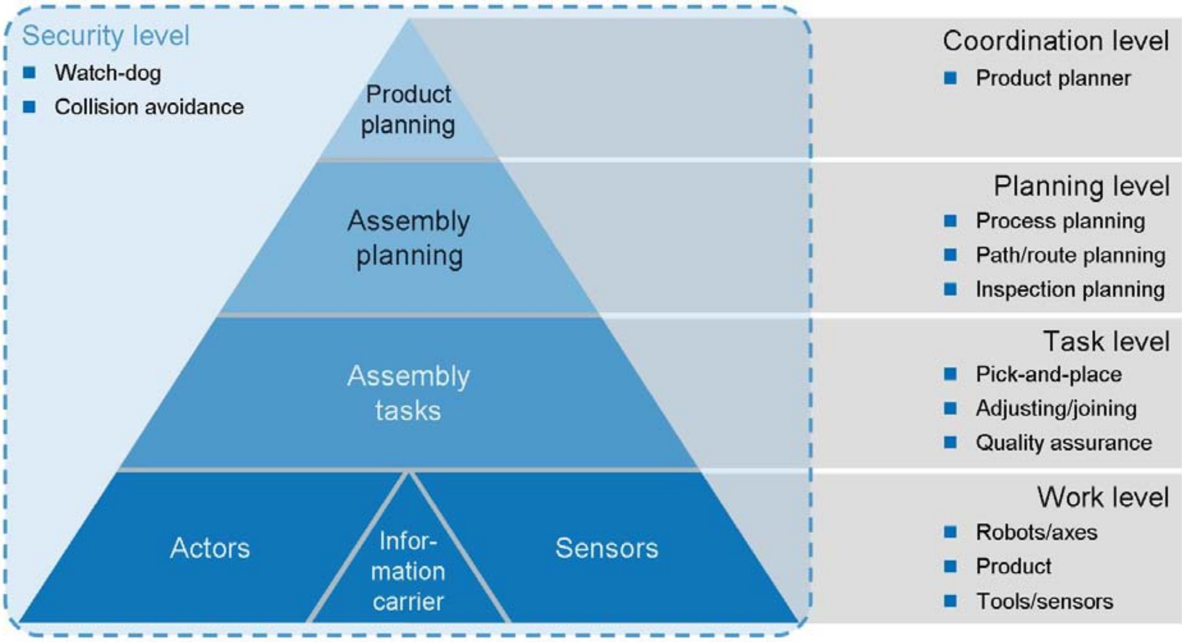

Fig. 8: Multi-agent hierarchical control structure for the self-optimized assembly process

It can be noticed that the upper levels (task, planning and coordination levels) are much more complex to be conceived and implemented. Some of these agents (planning and coordination) feature intelligent capabilities and need thus cognitive means and pro-active behavior, in order to deliberate about their actions and guarantee a safe and robust way to accomplish them. The agents of the lower levels usually do not need these cognitive capabilities and behave reactively to accomplish their activities.

In this sense, the hierarchical multi-agent control structure of the assembly system was conceived in a top-down approach, considering the different self-optimizing loops present already within the upper levels of the system, such as the planning of the assembly sequence, the planning of the robots' path and the inspection planning of the assembly [12].

Most part of the agents' tasks in the coordination and planning levels are performed based on software tools like simulations and classification methods. From the task level to the work level, the kind of agent task that is performed has much closer relationship with the control of hardware resources, as for example the manipulation, positioning, adjustment and soldering of optical components.

Although the conception and rough modeling of the assembly control architecture follows a top-down approach, the fine modeling and implementation of the individual agents of the whole system and their behaviors is developed using a bottom-up approach. This is needed because the agents of the lower level of the structure constitute the common and indispensable work basis for medium and high level assembly tasks. Another factor that contributes to this bottom-up development approach is the difficulty and complexity implementation degree of the agents in the upper levels.

Fig. 9 illustrates the common means for communication, organization and distribution of responsibilities of different assembly tasks among production agents, following specific standardization norms from FIPA (Foundation for Intelligent Physical Agents: http://www.fipa.org/).

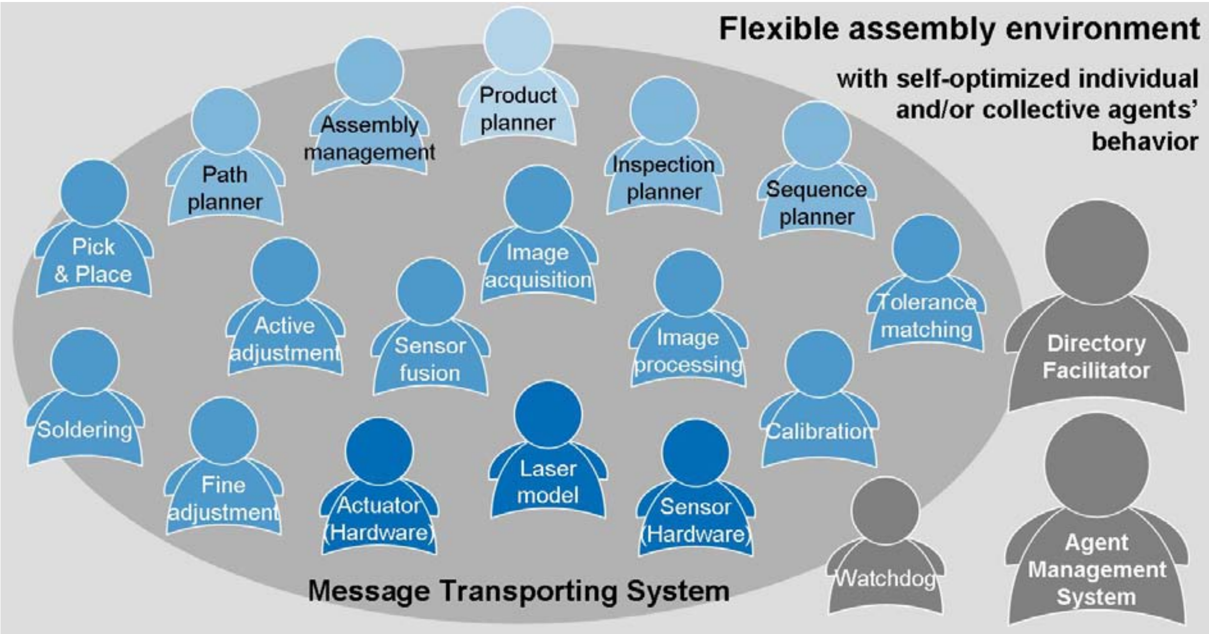

Fig. 9: FIPA-compliant multi-agent system for the self-optimized assembly process

4.2 Assembly sequence planning with MAS

As the optimal assembly sequence depends on performance specifications, component and assembly precision as well as available equipment and processes, planning can be a very complicated task that must be performed dynamically. The sequence planner now has the task to select an assembly procedure that will result in systems that meet different performance specifications simultaneously or, if infeasible, constitute a best compromise.

Because performance criteria are generally interrelated and depend on component positions as well as on component attributes that are subject to tolerance deviations, separate agents – each representing one specification – are implemented. Every agent possesses model-based knowledge about its associated performance criterion and can derive conclusions such as possible compensation of errors, necessary alignment or measurements. Rules define the agent's behavior to prevent the agent from finding undesired solutions and represent a generalization of the user's experience. For example, the ability to compensate performance deviations by adjusting component positions is extracted from the model and only the most significant compensators are considered.

The probability of achieving the desired specification based on a selected sequence is determined based on the model, while communication with agents of measurement equipment, robot cell and GUI provides necessary input for the selection of a valid sequence. By using multiple agents, optimal sequences can be flexibly derived and will be adapted with changing input. As new agents can be easily added, additional specifications or assembly tools can be integrated without complexity. In a first step to select an assembly strategy that is optimal for every specification, an agent is defined selecting a sequence that maximizes the compromise based on ratings of sequences developed by the feature agents. Alternatively, choosing the optimal sequence to meet every specification can be based on cooperating or competing agents.

5 Conclusion and outlook

Product individualization and global market pressure demand assembly solutions that feature high flexibility and yet display a high degree of automation. Planning efforts for the automated assembly of laser systems can be extremely high and demand new solutions in production automation.

In this paper an integrated concept for a self-optimizing assembly of laser systems is presented involving aspects of product design and process development as well as solutions for flexible robot cells in conjunction with multi-agent control systems.

On this basis different approaches towards self-optimizing assembly process are being implemented and demonstrated in the remaining course of the project.

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References

[1] Schuh G, Gottschalk S, Kupke D (2008) Individualisierte Produktion - Flexible Konfigurationslogik zur Gestaltung von integrativen Produktionssystemen. wt Werkstatttechnik online 4-2008, p 2

[2] Schmitt R, Pavim A, Brecher C, Pyschny N, Loosen P, Funck M, Dolkemeyer J, Morasch V (2008) Flexible automatisierte Montage von Festkörperlasern. wt Werkstattstechnik online 11/12, pp 955-960

[3] Dolkemeyer J, Funck M, Morasch V, Schnitzler C, Loosen P (2009) Soldering Techniques for the Assembly of High Power Solid-State Lasers. CLEO Europe

[4] Funck M, Loosen P (2008) Estimating the performance gain of selectively assembled optical systems. 53rd Internationales Wissenschaftliches Kolloquium, Proceedings

[5] Funck M, Loosen P (2009) Statistical simulation of selectively assembled optical systems. Optical Modelling and Performance Predictions, Proceedings SPIE Vol. 7427

[6] Frank U et al. (2004) Selbstoptimierende Systeme des Maschinenbaus: Definition und Konzepte. HNI-Verlagsschriftenreihe, Paderborn

[7] Dangelmaier W, Klöpper B (2009) Verhaltungsplanung für mechatronische Systeme - Planung als Funktion in selbstoptimierenden Systemen. wt Werkstattstechnik online, Jahrgang 99, Heft 3, pp 123-129

[8] Beierle C, Kern-Isberner G. (2006) Methoden wissensbasierter Systeme Grundlagen - Algorithmen – Anwendungen. Vieweg

[9] Schmitt R, Pavim A (2010) Eine Strategie zur dynamischen Planung und Durchführung der Montage von Lasersystemen. 7. Paderborner Workshop – Entwurf mechatronischer Systeme, Band 272, pp 99-114

[10] Russel S J, Norvig P (2003) Artificial Intelligence: A Modern Approach. Prentice Hall series in artificial intelligence, Prentice Hall/Prentice Education

[11] Jennings NR, Sycara K, Wooldridge M (1998) A Roadmap of Agent Research and Development. Autonomous Agents and Multi-Agent Systems 1, pp 275-306

[12] Brecher C, Pyschny N, Loosen P, Funck M, Morasch V, Schmitt R, Pavim A (2009) Self-optimising flexible assembly systems. Workshop on Self-X in mechatronics and other engineering applications, Paderborn, pp 23-38

[13] Göhner P, Urbano PGA, Wagner T (2004) Softwareagenten - Einführung und Überblick über eine Alternative Art der Softwareentwicklung. Teil 3: Agentensysteme in der Automatisierungstechnik. Automatisierungstechnische Praxis 46(2), pp 42-51