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Mechatronic Coupling System for Cooperative Manufacturing with Industrial Robots

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Abstract

Rising product variants and shortened product life cycles require more flexible and universally utilizable production systems and machines. Consequently, it can be expected that the importance of industrial robots in production will continuously increase, due to their suitability to take over the role of a universal production machine. However, robots are not yet able to fulfill this role. Industrial use of robots has so far been limited mainly to simple transport and handling tasks in the context of human-robot collaboration as well as highly repetitive automated tasks in the context of manufacturing and assembly. For universal use, robots must be capable to perform more demanding tasks in manufacturing with higher requirements on mechanical stiffness and accuracy. Therefore, this paper presents a mechatronic system to couple two robots to a parallel kinematic system to temporarily increase the mechanical stiffness. The coupled state of the robots allows load sharing, higher process forces and eventually higher precision. The overall goal is to enable robots to perform more demanding manufacturing tasks and thus to be utilized in a wider range of applications. Design requirements, the development approach and optimization methods of the first coupling module prototype will be presented and discussed. The next development steps, a future demonstration system and possible use cases for the coupling module will be shown in the outlook.

Keywords: Robot; Cognitive Robotics; Robot cooperation

1. Introduction

Fluctuating demand, shortened product life cycles and a greater range of variants of products create uncertain circumstances for the production technology of the future. Traditional production machines will not be able to achieve the flexibility required in the future. Thus, new adaptable production systems are needed. The concept of Wertstromkinematik (WSK) is a promising approach to design adaptable production systems [1]. It is based on the idea of designing the whole production system with unified robot kinematics which cover the entire value stream of a product. This includes not only the usual handling tasks in industrial robotics, but also manufacturing and assembly processes. As a result, the elimination of expensive, poorly adaptable specialized machines within a value stream greatly increases the flexibility of the production chain and simplifies rapid conversion to other end products. The reusability of production hardware brings both economic and ecological benefits.

The versatility of the production system correlates strongly with the flexibility of the robots regarding their fields of application. Therefore, a broad spectrum of applications of the deployed robots is a general requirement for such production system approaches.

Currently, typical industrial robots are primarily used for repetitive handling and assembly processes as well as simple manufacturing tasks (e.g. spot welding). Common manufacturing processes such as cutting or forming are reserved for specialized machines, as industrial robots are not suitable for these tasks due to their low mechanical stiffness and the resulting inaccuracy as well as the low process forces that can be applied. A promising approach, to significantly increase the mechanical stiffness and the manageable forces of industrial robots is the coupling of robot kinematics. The temporary linking of

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serial robot kinematics to form a parallel kinematic provides not only greater mechanical stiffness at the common TCP, but also a more homogeneous stiffness behavior in the common workspace compared to single kinematics [1]. As a result, the influence of the pose on the robot behavior is significantly reduced and therefore planning of applications simplified. The higher mechanical stiffness ideally also leads to higher accuracy due to the lower displacement of the common TCP by process forces. However, controlling this over-determined system is significantly more complex compared to a single robot. It is therefore not yet clear whether higher accuracy can actually be achieved through coupling. Further research on this will be necessary. Compared to other approaches to improve the stiffness and accuracy at the TCP, the coupling of robots also allows higher manageable process forces and load sharing capabilities when handling bulky and heavy objects. These benefits cannot be provided by software- or sensor-aided optimization approaches, and thus the coupling of robots offers a unique potential to enable new areas of application for robots.

This paper presents a novel prototype for coupling two serial robot kinematics. Section 2 presents the state of the art of coupled robotic systems. Section 3 describes the requirements and the development process of the new coupling module. In Section 4, the realised prototype is presented and evaluated. Finally, Section 5 discusses the potential of the coupling module and presents the next development steps and planned application scenarios.

2. Related work

In the field of robot-robot collaboration, a differentiation between pure cooperation, in which several robots share a common workspace, and actual collaboration, in which several robots also work simultaneously on the same object, is required. Research on cooperative interaction can be found in the field of dual-arm robots. In [2] a compliance control was developed on a dual-arm robot for a peg and hole task. [3] compared the performance of an industrial dual-arm robot with two single robots assembling a car dashboard. The dual-arm robot was able to achieve better workspace utilization and demonstrates easier feasibility of joint actions on the same object.

In the field of collaborative single-arm robots, a so-called geometric coupling is often applied. This means that several robots are synchronized with each other through an exchange of position and velocity data [4]. Today, all common robot manufacturers (e.g. KUKA [5]) offer software options for geometric coupling. Research with geometric coupling often focuses on simplifying the task planning of coupled systems, for example by programming the system via the end effector [6], instead of the individual robots, or by optimization through simulation and trajectory generation [7]. In the latter work, an experimental setup also demonstrated, that the coupled system can apply significantly higher forces than single robots, especially in a stiffness-optimized pose. Geometrically coupled robot systems are also used in cases like handling bulky parts or load sharing. A common application is the handling of large carbon fiber-reinforced parts in aerospace industry [8].

In [9] a workpiece-based trajectory programming of collaborating industrial robots holding and moving a stiff workpiece was presented. The results show that tightly coupled kinematics have limited capabilities if operated with geometric coupling. To leverage the full potential of coupled robots, force monitoring and control of internal forces and torques is necessary. This type of controlling, referred to as dynamic coupling, is often implemented using hybrid force or position control. Position control is used to ensure path accuracy, while force control is used to regulate internal forces and torques [10].

Despite internal force control, additional compliant elements are often integrated in systems with tight coupling. In [11], two robots are coupled by a rigid workpiece with an integrated force sensor and rubber springs. In [12], a rigid workpiece is gripped jointly by two robots. One of the robots has a spiral spring integrated between its flange and gripper. [13] shows coupling through an aluminum can with no additional compliant element using a fuzzy controller. [14] also realized a rigid coupling without compliance using an impedance controller. In [15] an approach is described in which a cobot docks directly to any joint of another cobot to support handling processes.

In research with coupled robots, force-based control strategies, in particular hybrid force and position controllers, impedance controllers and compliance controllers relying on force sensors attached to the robot flange, have become well established. However, most approaches rely on additional passive compliant elements in the kinematic chain. The presented research mainly shows handling tasks, in which the manipulated workpiece itself serves as coupling element. A separated coupling element, which enables coupled actions independent of the specific workpiece, is not considered. The use of coupled systems in manufacturing scenarios, associated with increased accuracy requirements as well as process force disturbances, is also not examined.

3. Development and design of the coupling module

As explained in Section 1, the premise of Wertstromkinematik is the universal applicability of robot kinematics in an adaptable production system. This includes the coupling of multiple kinematics for different tasks that go beyond the usual applications of industrial robots. To enable a range of operations, various end effectors will be used. Therefore, an adapter-based concept for the coupling is suited to ensure independence of the coupling function and the manufacturing task. The aim of the presented work is the development of such a coupling system for industrial robots, hereinafter referred to as coupling module.

3.1. General conditions and assumptions

Requirements for the coupling module emerge from the previous considerations. First, the collaborating robot kinematics must be mechanically connected via the coupling module. The

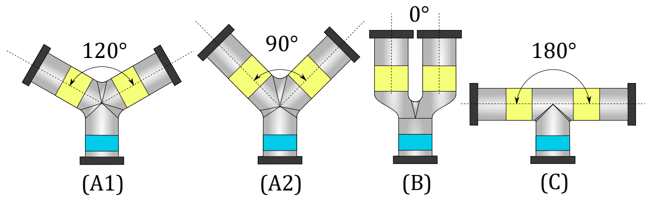

Fig. 1: The four basic shape concepts

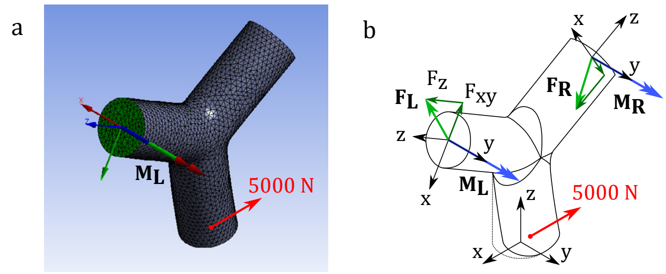

Fig. 2: Left arm reaction moment M_L (a) and schematic illustration of all reaction forces and torques for an exemplary load (b)

workpiece nor the tool are part of the coupling mechanism, contrary to the approaches mentioned in Section 2. Furthermore, measurement of internal forces must be possible and compliant elements help implementing a force-based control strategy of the coupled kinematics. Due to the wide range of applications, the coupling module should be compatible with as many different end effectors as possible through a standardized mechanical end effector interface. In the prototype stage many changes to the initial design are expected and therefore a modular structure of the coupling module with replaceable components is suggested.

3.2. Shape and dimensioning

To narrow down the relevant load range and define basic dimensions of the module, manufacturing use-cases from milling and sheet bending are analysed. The most influential variable is the process force. It directly affects the dimensioning of structural parts and the purchased components in the line of forces.

The first estimate for the maximum process forces at the TCP is derived from exemplary milling applications. With the formulas presented in [16], estimated cutting forces are calculated. For comparison the values are also inserted in the formulas from [17] for sheet metal bending. For the first prototype of the coupling module the use case limit of the process forces is set to 5000 N, including a safety factor.

The coupling of two robots and the attachment of a tool require three mechanical docking interfaces. Four shape concepts with different orientation angles are developed and analyzed (Figure 1). The orientation angle between these interfaces is variable and highly influences the force transmission from end effector to robot flange.

The selection of the most suitable arm angle is determined with a finite element analysis. A simplified model of the coupling module is loaded with the maximum expected operating loads in alternating directions (Figure 2). This results in a total of 18 different load cases, as shown in Figure 3. Gravitation is not considered, because the orientation of the system is not predetermined.

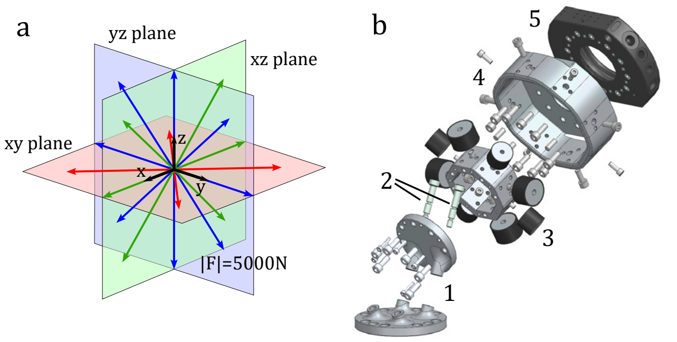

Fig. 3: Overview of load cases (a); explosion view of the right arm (b)

The maximum reaction forces and moments exerted in the fixed constraints in the two robot flanges can be compared. Figure 2, for example, shows the reaction moment in the left arm for a load in negative x-direction at the TCP. Minimization of reaction forces and moments is the principal criterion for the selection of a suitable concept. However, minimal moment loads are favored, since sensors and quick-change systems are particularly sensitive to moment loads. Furthermore, compressive loads are considered less critical than tensile loads. A cost-utility analysis of the various concepts shows that an angle of 120° between the arms is an optimal compromise for varying load cases.

3.3. Modular structure and components

To provide the desired modularity, the components of the coupling module are bolted together with flange joints. By using detachable connections, changes in the test phase can be implemented quickly.

The coupling procedure must be automated and safe. Quick-change systems, which are already established in automation technology, are ideal for this purpose. These can couple an end effector pneumatically to a robot. The coupling locks the position of the two flanges in relation to each other with repeatability. In case of pressure failure, emergency operation is ensured by self-locking. An important aspect of the coupling interface is the feed-through of signals and process mediums such as measurement and control signals, electrical power, compressed air and fluids. For this purpose the quick-change systems are equipped with so-called feed-through modules.

The main purpose of coupling several kinematics is to increase mechanical stiffness, by temporarily forming a parallel kinematic structure. However, since current control concepts are not designed for a rigid connection of two robots, some compliance of the coupling module must initially be accepted. This counteracts the bracing forces caused by position and path inaccuracies of the individual robot kinematics. The

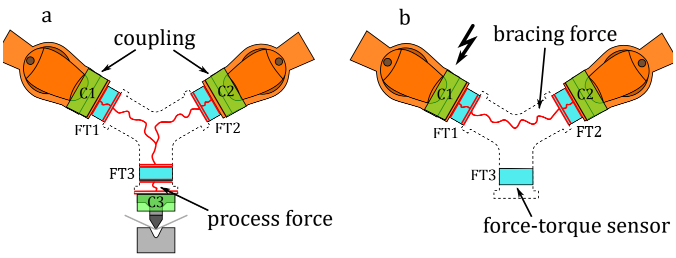

Fig. 4: Force flow of process forces (a) and the bracing forces (b)

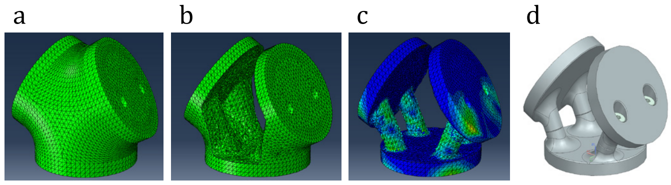

Fig. 5: (a) model before optimization; (b) target volume $x = 50\,\%$; (c) target volume $x = 37\,\%$; (d) final CAD model.

necessary compliance module should be adjustable and must provide compliance for all translational and rotational degrees of freedom. In order to achieve the required flexibility of the system, a spring system is proposed (Figure 3). Standard rubber buffers as described in DIN 95363 are used for this purpose. Their suitability for this application was tested experimentally in tensile and shear tests. The tests have shown that the springs exhibit an approximately constant stiffness within certain limits for compression, tension and shear loading. Using these stiffness characteristics and a stiffness model of the robot kinematics, a first target stiffness for the compliance module can be determined. Adaptive stiffness of the compliance module can be achieved by replacing, reconfiguring or changing the amount of rubber buffers.

The core of the modern control concept is the low-stress control of the supporting kinematics. This is achieved by continuously monitoring the process and bracing forces. For this purpose, force-torque sensors must be integrated into the structure of the kinematic chain, see Figure 4. A single force-torque sensor in the lower arm of the coupling module (FT3) will be used to identify the proportion of process forces of the total measured forces at the robot flanges.

3.4. Concept assessment and optimization

An assessment of the first concept of the coupling module has shown the need for optimization in some points. In the following weak points are addressed and improvements are highlighted.

Weight reduction. The most important optimization aspect is weight reduction. Due to adjustments of components in the coupling module, the dimensions of the arms and consequently the levers change, which has a large influence on the resulting moment loads. Thus, the following iterative optimization process is proposed. First structural parts are adapted and the finite element analysis is updated with the new model. Then component selection is adjusted to the recalculated maximum loads. This way the weight of the coupling module was drastically reduced.

The weight of the central connecting element of the coupling module, which will be called the ”star element” in the following, was reduced by means of topology optimization. For this purpose, a finite element model of the star element is created. The flange regions and a volume around the breaking point are excluded from the optimization. The optimization goal is to minimize the sum of strain energies over all 18 load cases (Figure 3). The target volume is given as $x = 37\,\%$ of the initial volume and the maximum von-Mises stress must not exceed the yield strength of the material with a safety factor $S = 1.5$.

Figure 5 shows the initial geometry of the star element before topology optimization. The core material is not loaded and thus quickly removed by the optimization algorithm. The component is also cut into three parts to integrate the predetermined breaking points and simplify manufacturing.

Predetermined breaking points. The predetermined breaking points need to be integrated as a safety mechanism and for overload protection of the components and the robot joints. It is located in the star element. The two upper arms are allowed to disconnect at the center of the coupling module if the forces are too high. This breaks the coupling and the force flow is interrupted. The proposed predetermined breaking point allows operation to be resumed in a short time and the failure should not cause any permanent deformation to the structure of the coupling module. The predetermined breaking point in the coupling module is realized by bolts connecting the upper arms to the star element (Figure 3). These bolts fail before the structure of the coupling module is plastically deformed or the sensors as well as the quick-change systems are damaged.

4. Results and evaluation

4.1. Final structure and its components

A prototype of the coupling module (Figure 6) was manufactured as part of the Wertstromkinematik research project. The prototype will be used in a robot demonstration cell to achieve larger forces in sheet metal forming by coupling two robot kinematics.

Quick-change modules. The quick-change interface used is the SWS-160 from SCHUNK. The coupling procedure of both arms is controlled by a central PLC group. There are feed-through modules for the signal lines of the force-torque sensor and for further signal lines that may be needed by additional end effectors. Pneumatic feed-throughs are integrated into the SWS. For high-power electrical end effectors, such as milling spindles, a separated power feed-through with according electrical specifications is available. In addition, a self-sealing fluid feed-through module can also be used to route cooling liquids to end effectors.

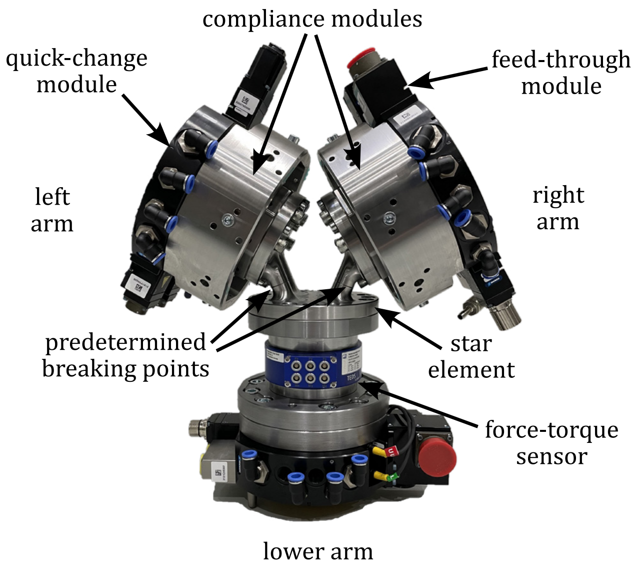

Fig. 6: Coupling module prototype

Force-torque sensors. The MCS10-100 from HBK is used for force and torque measurement. These sensors meet the large load requirements that occur in certain coupled applications. Signal processing is handled by a PMX amplifier system from HBK. The high sampling rates of up to 38.4 kHz and synchronous bus interfaces allow effective force control of the robot kinematics.

Predetermined breaking points. The predetermined breaking points consist of custom machined fitting screws. Due to the fits, the connected arms of the coupling module are precisely positioned in relation to each other. A notch in the fitting screws serves as the predetermined breaking point.

Compliance module. The spring system is reconfigurable by arranging different rubber elements. In this way, various target stiffnesses can be set. The required ratio between axial and radial stiffness is achieved by radially distributing multiple rubber elements. Adjustments can be made by using rubber of different shore hardness and diameter, as well as rearrangement of elements.

4.2. Evaluation

The function density of the coupling module can be increased. By moving, for example, signal processing or pneumatic switching inside of the system boundaries, the necessary complexity of the surrounding production system could be reduced. Of course, this would be accompanied by an increased weight due to additional components.

The compliance module takes up a large part of the volume of the overall system. There is optimization potential for the mass of the coupling module. In addition, the currently set compliance characteristic of the compliance module is very soft.

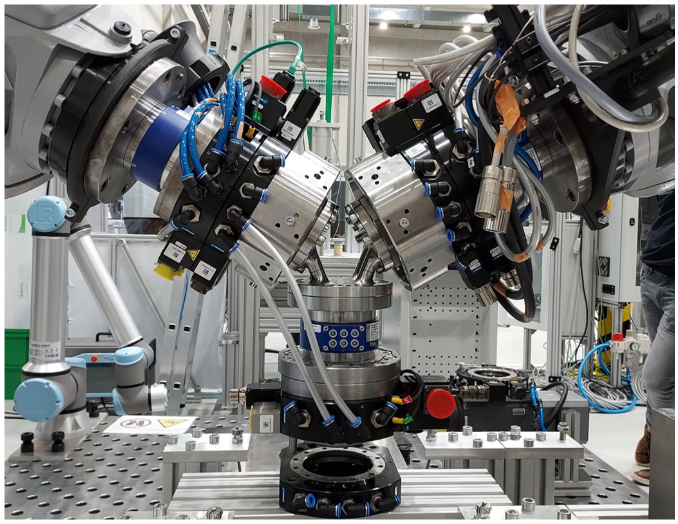

Fig. 7: Initial successful coupling tests show internal forces of 500 N

The compliance must be reduced in the course of further developments until the overall mechanical stiffness of the coupled kinematic chain is higher than stiffness of a single robot. So far, there is no model for the behavior of the compliance. With the help of such a model, the deformation could be compensated. Likewise, the effects of aging, heating and creep of the compliance system have not yet been exhaustively examined.

Furthermore, lightweight design methods, such as systematic material selection or structural optimization, can reduce the overall weight of the coupling module even more.

5. Integration and outlook

The coupling module is integrated into a robot cell. The robot cell serves as a test platform for testing and further developing the coupling module. This robot cell contains two Comau NJ290-3.0 industrial robots with a individual payload of 290 kg and a range of 3 m. The robots are each controlled by a SINUMERIK ONE numerical controller by SIEMENS. A sheet metal forming stamp, a suction gripper and a milling spindle are available in the cell for future use of the coupled robot system in manufacturing operations. These end effectors can be connected to an individual robot as well as the coupled system using the coupling module.

Initial coupling tests were carried out with a soft compliance configuration. It has become apparent that the coupling module must be positioned and oriented very precisely in the cell to prevent excessive stresses during the coupling process and to avoid failure of coupling attempts. First successful coupling attempts with a soft compliance configuration show internal loads of around 500 N (Figure 7). Stiffer compliance configurations will quickly result in loads that are too high for the robot joints. Possible optimization steps to reduce the initial stresses include calibration of the robots relative to each other, compensating the weight-based deflection of each robots TCP and controlling of both robots via a common NC controller using 12-axis interpolation to improve the synchronization.

A further challenge is the integration of various end effectors. The proposed coupling module defines the mechanical and electrical interface between the universal robot and exchangeable end effectors. Each end effector contains different sensors and actuators, which need to be connected to data processing units at the robot base. Due to the variety of communication protocols used for actuator control and sensor readout, the limited number of electrical signal lines provided by feed-through modules may not suffice to realize the communication interfaces required by all end effectors in parallel. Solutions to overcome this issue include the selection of few generic communication protocols for use at the robot-end effector interface and, consequently, the integration of protocol conversion units with end effectors that host components requiring different protocols. Alternatively, a protocol multiplexing approach has been researched as part of the Wertstromkinematik project that allows for implementing multiple communication protocols over shared signal lines [18]. By reconfiguring the mapping of communication protocols to signal lines on end effector exchange, it can help to reduce the number of signal lines required at the interface.

After completion of the planned integration tasks, the next step will be the integration of a hybrid force and position controller that compensates the internal forces via the force control and ensures the path accuracy along the trajectory via position control. The control system should enable the coupled system to move with high dynamics and, in the long term, replace the spring systems in the coupling module to achieve a significantly higher overall mechanical stiffness of the coupled robot system. After integration of the control system, a comprehensive series of tests to quantitatively evaluate the potential of the coupling system is planned. The potential of this overall setup will also be experimentally determined in sheet metal forming and milling processes.

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