Software-defined testing facility for component testing with industrial robots

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***Abstract*—A key aspect of industry 4.0 is the transition of production to batch size one and consequently unique dimensions and structures of components for each product. Since many components are only available in small quantities it is not feasible to design expensive test benches for each of these components, however it is still important to test them to ensure the quality of each individual component. Therefore, we propose an approach for a flexibly programmable robotic test bench for destructive component testing of various components. This includes a concept for planning and execution of different test movements in a component test on robotic test benches and a unified data platform for controlling sensor-based motions as well as the recording of test data.**

***Index Terms*—Industrial Robots, Destructive Component Testing, Robot Modeling, Robot-based Testing**

I. INTRODUCTION

Production is in a state of upheaval due to industry 4.0. The goal is to produce individual products in small quantities with the same or better quality than with conventional manufacturing. With the conversion of production to batch size one [1] and consequently unique dimensions and structures of components for each product, it must also be possible to flexibly adapt the testing of components. Furthermore, due to the increasing complexity of components through additive manufacturing, for example, the test setup of components is also becoming more complex. Since many components are only available in small quantities, it is not profitable to design expensive test benches for each of these components, but it is still important to test these components to ensure the quality of each individual component.

Component testing is divided into two types. There is destructive component testing (DT) in which a component is tested until it deforms irreversibly. This is used to determine performance or material behavior of a specimen or component under extreme conditions (e. g. high forces, high temperatures or high acidity). The second type is non-destructive testing (NDT). NDT aims to test components without destroying them, so that they can still be used for their intended purpose. Examples of NDT are radiographic, ultrasonic, or visual testing. In the further course, the focus is placed on DT with fracture and mechanical testing, a process in which high forces and torques are applied to tensile specimen and components until they fail [2]. In order to destructively test a large number of components with high forces and torques, a flexible test setup is required that can be adapted to different component tests. Standard testing machines are usually only able to perform simple movements or are mostly specially designed to meet the test requirements of the component. For these reasons, a concept to perform robot-based destructive component testing for various components was developed. Due to the high number of movement directions (six degrees of freedom) and the large working range of a six-axis industrial robot, it is possible to apply forces and torques to different products and also perform complex test movements on the component. This paper has the following contribution to the implementation of destructive component testing by industrial robots:

1) Flexible software-adapted robot-based test bench for destructive component testing of various components
2) Concept for the planning and execution of component tests in robot-based test benches with different test movements
3) Unified data platform for control of sensor-based movements and the recording of the test data

The paper is divided into six sections. Section II summarizes the current state of the art in robotic testing and provides an overview of data interfaces for control and recording of test results. The approach for planning and executing component tests is explained in Section III. Section IV describes an example of a flexible robot test bench. The evaluation of the robot test bench in comparison with classical testing machines is shown in Section V. Section VI draws a conclusion.

II. STATE OF THE ART

In addition to the above mentioned two types of component tests, destructive and non-destructive, there are also two different methods of using robots for component testing namely robot-assisted and robot-based methods. The first type is characterized by a combination of a stationary test machine with a robot, e.g. in automated tensile testing, where the robot loads the specimen into the testing machine [3]. In comparison robot-based approaches are mainly performed by robots with

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other testing machines merely in a supporting role. Nowadays, robot-assisted and robot-based approaches are predominantly used in the field of non-destructive material testing. They are standard in manufacturing industries and production plants and are typcially used for in-line monitoring of clearly defined material or product properties, e.g. to check the tolerance or the quality of automotive resistance spot welds [4]. The interface between robot-assisted and robot-based in destructive and non-destructive material characterization plays an important role in medical technology. The use of robots in this area offers the advantage of implementing realistic load cases under physiologically and reproducible conditions as they are able to mimic human body movements, e.g., chewing motions [5], knee joint motion sequences [6] or for the analysis of the stability and thermal wear of dental adhesive materials [7]. A first approach for robot-based destructive component testing is a test rig concept in form of a hexapod, also known as Stewart platform, which allows six degrees of freedom (DoFs) due to its six legs which are each able to vary in length independently. Several universities are conducting research on this topic, for example, Hamburg University of Technology (Germany) [8] or the University of Cachan (France) [9]. This hexapod concept is especially suitable for the determination of the fatigue strength of components and large structures. In addition to service life and fatigue tests, static and dynamic stiffness and damping measurements can be performed. The components to be tested are mounted between a fixed load cell and an overlapping movable platform to apply multi-axial loads up to 500 kN. Although this approach achieves high loads, it is at the same time severely limited by its construction, due to limitations in the size of the test components and restricted range of motion. Finally, it should be noted that the application of superimposed loads with special testing machines (e.g. via biaxial systems or superimposing tensile and torsional loads) is also already possible. For these complex, multi-axial loading conditions, special testing machines or set-ups are required, which are usually not very flexible. Therefore, only a few selected load cases can be represented or specific component sizes can be tested. In addition to the distinction between robot-based and robot-assisted, different technologies for controlling and data acquisition of sensors and actuators are needed. The OPC Unified Architecture (OPC UA) is a vendor-neutral, service-oriented architecture that ensures platform independence, security, rich information modeling as well as a holistic communication protocol. It is based on a client-server infrastructure and with its integrated information model, every server is able to organize data or methods in a standardized way [10]. With part 14 of the OPC UA specification, introducing the many-to-many communication based on the publish/subscribe (PubSub) mechanism, OPC UA offers the possibility for multiple subscribers to receive the same data messages as well as the advantage of being reconfigurable during runtime [11]. Many sensors and actuators require real-time communication to ensure defined timing constraints, e.g. a motion controller with a specific cycle time. To ensure time-deterministic communication the OPC UA PubSub over TSN approach was introduced [12]. This approach enables a uniform and universal network convergence with timing guarantees by extending the ethernet protocol developed within the IEEE 802.1 Working Group [13]. By combining all of the aforementioned technologies and research projects we are, to the best of our knowledge, the first to present a novel robot-based concept and facility for destructive mechanical component testing with two cooperating high payload industrial robots and additional sensors and actuators.

III. CONCEPT

To make the complexity of robot-based destructive component inspection manageable and to ensure test reproducibility, a standardized test procedure consisting of three phases as shown in Figure 1 is proposed. The first phase is used for the test case *preparation*. This includes the analysis of the component, the determination of the test motions and the resulting placement of the test component in relation to the robot. In addition, the sensors for evaluation are determined and, if necessary, a simulation is performed. In the second phase (*execution*) the actual component test is carried out. In the final phase called *postprocessing* the recorded test data is processed and evaluated.

A. *Preparation Phase*

The first phase, the preparation phase, consists of five steps and starts with the *component analysis*. This first step handles the definition of the component properties, which will be later described in detail, as these will later influence the further course of the test procedure. In order to be able to decide where to place the component on the clamping area, the possible fastening points on the component must be identified. If it turns out that the component cannot be placed directly on the clamping field, suitable clamping devices must be designed in this sub-step. After the component can be fixed to the clamping area with this information, the basis for the test motions still have to be identified. This includes the material properties and the so-called loading points. Material properties define the selection and type of test motions and loading points specify where a force or torque is to be applied directly to the component. With this basis, the test motions can now be modeled in the next step (*testing motion definition*). Basically we distinguish between *approach*, *testing* and *departure-motions* for the robots or for additional actuators, e.g. linear actuators. Approach-motions can again be divided into position-based and contact-based motions. Within the position-based approach-motion the end-effector is moved to the desired loading point with a position controller. This can be achieved either with the help of the robot's internal positioning system or with an external position measuring systems, e.g. 3D-cameras. In contrast, the end effector within a contact-based approach-motion is positioned with a force controller. For example, when moving to a previously defined loading point, all lateral forces can be regulated to zero and only one force direction can be set to a specific value. This ensures, for example, that the end effector is exactly

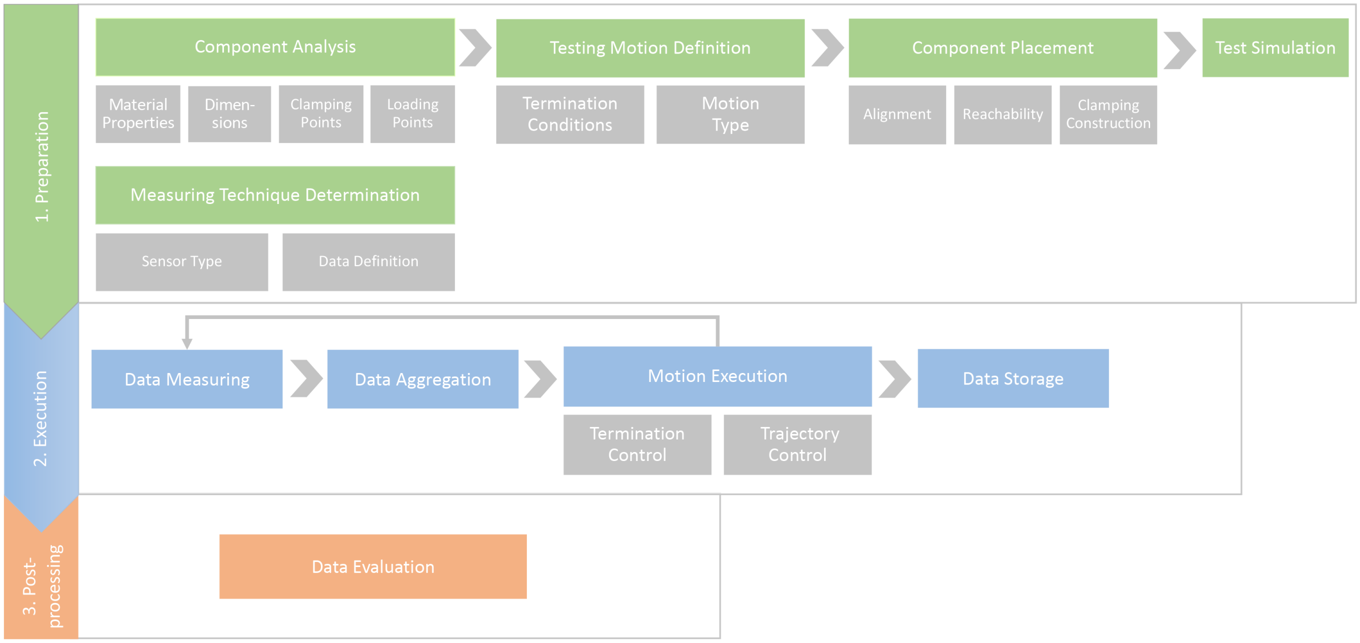

Fig. 1: Standardized test procedure consisting of three phases. This first phase defines the *preparation* of a test case. The second phase (*execution*) illustrates how the actual component test is carried out. In the final phase called *postprocessing* the recorded test data is evaluated.

orthogonal to this previously defined direction. Within the test motions we distinguish between multiple types, defined by their corresponding load vectors, which can be modeled as illustrated in Figure 2. A test motion consists of one or more load vectors. Each load vector is defined by a load vector type that specifies the regulation mode. For example, a test motion can consist of both a force vector and a torque vector. In this way, both superimposed loads and classic test motions can be modeled. In addition to the control mode, a load vector is also defined by its respective termination criteria. These criteria are important for deciding whether a test motion is completed and the entire test is finished or that the next test motion can be executed. These five criteria have been identified: maximum force, maximum torque, maximum time, maximum distance and fracture. The first four are simple abort criteria which can be represented by only a value or vector i.e. the maximum force in kN in a specific direction. Furthermore, it is important to detect whether the tested component fails, e. g. if the object breaks, the robot would continue to move in the given test direction at high speed, due to the high energy potential. The fracture is defined by a significant load drop with respect to the preceding maximum load. At a drop of a defined percentage, usually 20%, a break is suspected and the criterion is met. As soon as all test motions are completed the departure motion is started. This motion performs a slow unloading of the component, which was loaded by test movements performed before. If a fracture has occurred, this motion can automatically position the robot at a point defined in advance, e.g. the starting point. To determine which test motions have to be executed, the sequence of execution is also important. We propose a modeling approach for this using the syntax of UML state machines. This way, the individual motions can be represented as successive states. Swim lanes can be used to differentiate between multiple devices and also show concurrent motions. Interrupt-based termination criteria can thus be modeled as triggers. For illustration purposes we have listed a small example that performs a test case with two robots (see Figure 3), one on the left swim lane (R1) and the other

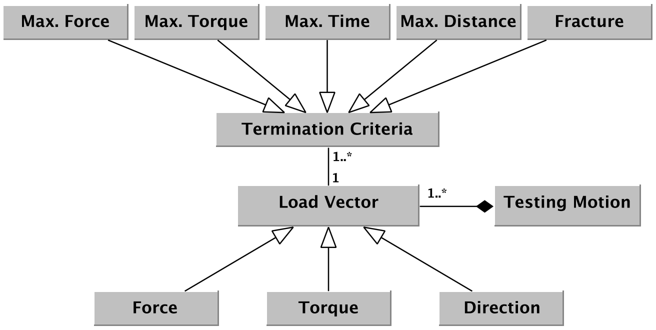

Fig. 2: Modeling of testing motions. Each motion is defined by a load vector and equipped with one or more termination criteria.

on the right (R2), with three different testing motions and one departure motion for each robot. At the beginning, the two robots each perform their approach motion with the respective termination criterion (TC). As soon as both have completed their approach motion, the subsequent test motions are started. Robot 1 performs two test motions and robot 2 performs one test motion. As with the approach motions, the transition between the individual states is controlled by the termination criteria as interrupt-based triggers. In addition, an overriding abort criterion can be introduced for execution of the testing motions to immediately initiate the departure motion (TC 6), e.g., if an early break occurs. The sequence is completed as soon as both departure motion termination criteria (TC 7, TC 8) are fulfilled. After defining the testing motions properties, the execution order and performing the component analysis subsequently the *component placement* can be chosen. When selecting an optimal placement for the component a large number of geometric configurations, load vectors and testable component sizes for each robot must be considered. At the same time, this geometric flexibility also poses an intrinsic optimization problem, since a specific load vector can be achieved at a certain position in the workspace in almost any number of robot positions. Therefore, a software supported component placement must take place. To predict the optimal position, a static force analysis model was developed and combined with a mixed reality commissioning tool. This tool enables quick and intuitive component placement and alignment using an optical see-through head-mounted display, e.g. a HoloLens from Microsoft [14]. These steps (component analysis, testing motion definition and component placement) form the basis for the simulation step (*test simulation*). With this approach it additionally becomes possible to simulate the complete process, starting with the approach motion, through the successive test motions, up to the departure movement. Simulation of the testing motions movements can also be combined with a simulation of the material properties (Finite Element Analysis FEM) in order to carry out a comparison with the material inspection actually performed in the next phase. A possible simulation environment e.g. would be Isaac Sim from NVIDIA [15]. Finally, to determine the material behavior of the test component under load, additional sensors can be used. Acoustic emission or digital image correlation, for example, offer the opportunity to detect damage on the micro and macro scale depending on the load, to locate it spatially and to classify the type of damage [16], [17]. It is important to define the performance characteristics of the sensors, especially the amount of data and the frequency, beforehand, in order to integrate them into the superordinate measuring and data aggregation concept. With this last step, the preparation phase is completed, which means that the actual component test can now be started.

B. Execution Phase

The second phase, the execution phase, consists of five main steps and starts with the *data measuring* step. In this step the data of the previously defined sensors and actuators are measured. Since the data from the sensors and actuators are measured at different frequencies, they must be aggregated in the next step, called *data aggregation*. This aggregation is important to provide the data in the next step for *motion execution*. In this step the previously modeled movements are executed and the termination criteria are monitored. In addition, a cyclic execution takes place, since the measured values of the sensors naturally influence the motion, in order to perform possible readjustments. This phase is completed with the last step, the *data storage* of all measured data. In order to manage the execution phase a superordinate architecture concept was developed, which is shown in Figure 4. This approach exploits the various advantages created by a client/server architecture using the PubSub mechanism as communication basis. In this way, additional devices can be added irrespective of the manufacturer to the existing infrastructure. These devices only need to be integrated into the main control component. It is responsible for the control of the actuators (motion execution), the data aggregation as well as the data storage. This component is encapsulated in its own OPC UA Client, which is connected to the other components via ethernet. Analogously, each sensor and actuator is also encapsulated in its own OPC UA Server. Each component has its own information model and only the control component

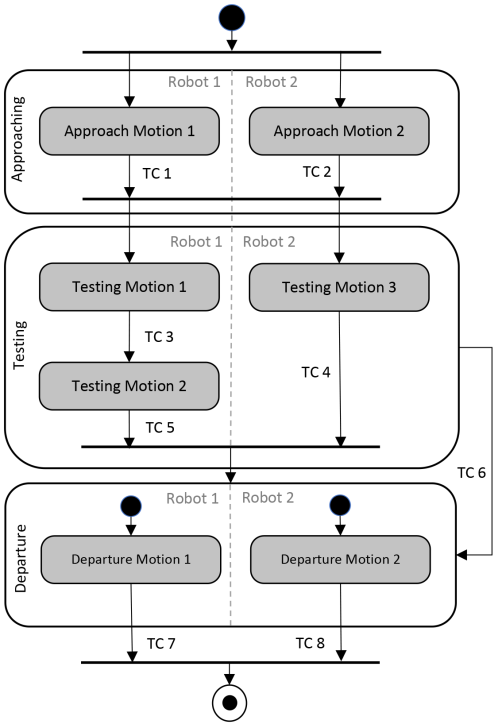

Fig. 3: State machine for the description of an exemplary motion execution sequence. The sequence for both robots start with two approach motions, followed by the test motions and ended by the departure motions.

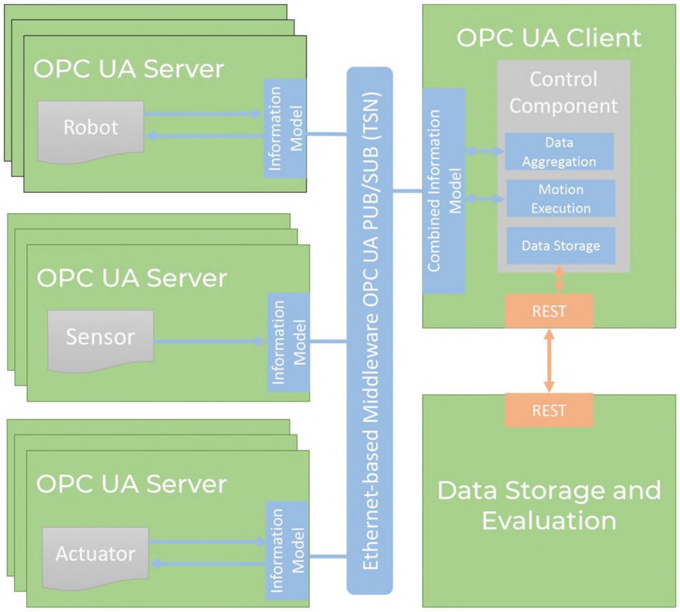

Fig. 4: Superordinate architecture concept, which consists of the main control component and additional actuators and sensors as well as the data storage. Since robots play an elementary role in the concept, they have explicitly not been represented as actuators. All components are encapsulated in OPC UA Servers and communicate via a ethernet-based middleware.

must have an aggregated information model. This encapsulates the proprietary interfaces of the individual devices and the overall system can be easily expanded with additional sensors or actuators by making use of this standardized mechanism. For the ethernet-based communication the PubSub mechanism provided by OPC UA with or without TSN was used. Via this middleware the sensor or actuator data can be subscribed to and processed by the control component. Moreover, the control commands can also be published via this middleware and subscribed to by the robots or other actuators. Furthermore TSN provides the relevant features for robot control in order to achieve real-time communication goals. The clock synchronization, which is relevant for data aggregation later on, is possible via this middleware. We have already developed a mechanism for the robot control and clock synchronization via OPC UA TSN in our recent publication [18]. Finally, the control component communicates via REST with the data storage and evaluation component. As an open source trial data storage and preparation platform the tool Shepard from DLR (German Aerospace Center) [19] has proven suitable in the first test. However, with an open REST interface, other storage and evaluation tools can be used.

C. Postprocessing Phase

In the third phase, the *postprocessing phase*, the aggregated data is finally evaluated and visualized. This includes especially the storage of the recorded test data with the association to test and component. Also, the stored data can be used to optimize the load paths or the test motions of following tests.

IV. TESTING FACILITY SETUP

As part of the WiR Augsburg project [20], a new test facility was designed and implemented (see Figure 5). The basis is a 7 m x 2.5 m clamping field ①, on which a linear testing cylinder (EZ100) from ZwickRoell ③ and a clamping angle ④ as counterpart for axial force application are mounted. This field enables the flexible fastening of very small to large test objects in any position, whereby the position of the clamping angle and the linear cylinder can be varied depending on the geometry of the test object. The core of the test facility are two KUKA KR1000 Titan robots ② with one tonne load capacity each, which are used to apply forces. These 6-axis industrial robots offer a high degree of motion flexibility (6 DoF). Using this motion flexibility enables the testing of different types of components, e.g. in sizes from small to large with varying geometries. In contrast to a conventional arrangement on a clamping field with fixed clamping elements and linear actuators the robotic systems can introduce loads from different directions at different positions in the test space and superimpose torsional forces almost arbitrarily. This concept enables in general, to test all structures that fit onto the clamping field. Limitations arise mainly in the geometry of the structures. If the components are too small, the robots may obstruct each other. These problems can be solved by means of appropriate end effectors. On the other hand if the structures are too large, the problem occurs that they cannot be clamped onto the intended clamping field or the reach of the robots may not be sufficient to apply loads that are high enough to carry out meaningful tests. The possible workspace of each individual robot as well as the common workspace is illustrated in a top-down view on the right in Figure 5. In addition, the positions that the robots can reach and where forces or torques can be applied are illustrated as circles on the clamping area. Each circle has a diameter of 2.8 m. This gives an initial indication of the component size up to which testing can be carried out. However, it is also strongly dependent on the component and the position of the load application points. A natural maximum size is given by the distance between the two robots. If a component exceeds the width of 2.5 m or a height of 2.4 m and a rotation of this component is not possible, it cannot be tested. For material characterization as well as for the motion execution and motion adjustment, additional sensors were integrated into the system. Both robots are equipped with 6-axis-Force-Torque-Sensors K6D175 from ME-Messsysteme and are used with the GSV-8DS EC/SubD44H measuring amplifier. These have a measuring frequency of 250 Hertz and provide their data via an ETHERCAT interface. With these it is possible to measure forces up to +/- 100 kN in z-direction and to measure forces in x- and y-direction up to +/- 50 kN. In addition, it is also possible to measure torques up to 10 kNm in z-direction and torques up to +/- 5 kNm in x-direction and y-direction. Whereas the z-direction represents the motion vector of the

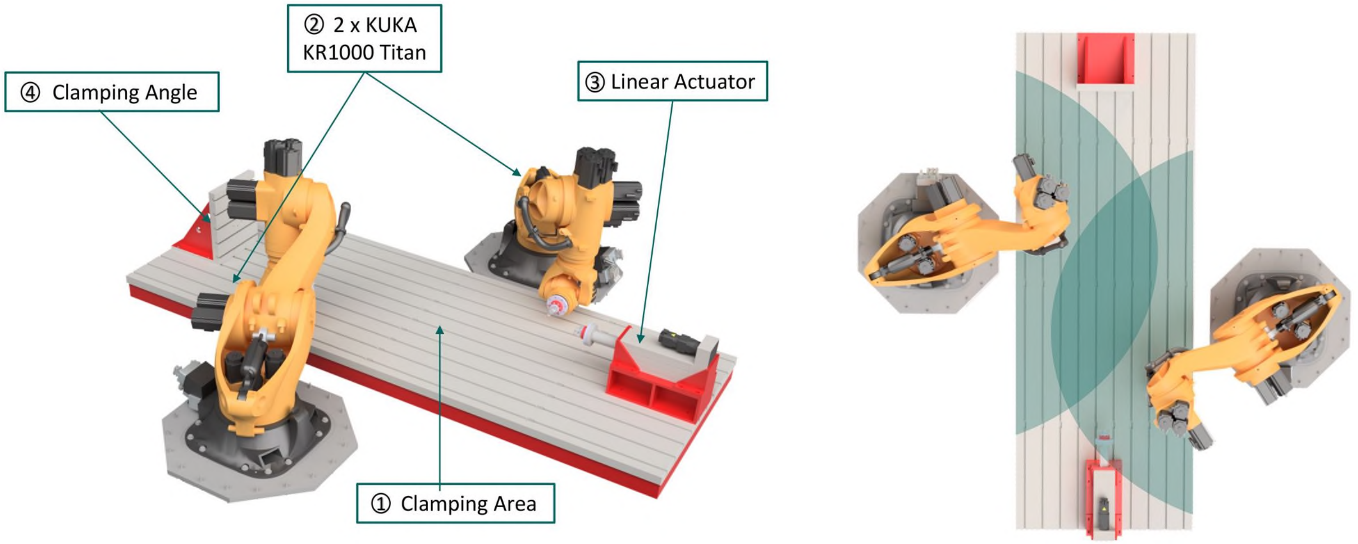

Fig. 5: The facility for mechanical component testing on the left consists of a clamping area (7 m x 2,5 m) for the flexible positioning of testing components, two KUKA KR1000 titan robots, an electromechanical testing actuator from ZwickRoell with its counterpart. On the right the workspace for each robot as well as the common workspace is illustrated with two circles.

robot and it is a right-handed coordinate system. To provide further valuable information for material characterisation and components behavior a digital image correlation (DIC) system is included into the experimental setup. The usage of these systems in the context of component testing is well established and a common occurrence [17], [21]. The used ATOS5 system manufactured by Carl Zeiss GOM Metrology GmbH provides high-precision 3D metrology data. This system can be used with different measurement volumes and resolutions by switching lenses. This gives the opportunity to inspect different test component sizes, which fit in with the variable test facility concept. The used software for this device is called ARAMIS Professional. For further live processing of the data during an experiment two options are available. Option one logs the internally calculated values, e.g. points in the test space, to a local protocol file, constantly updating during the experiment. Option two provides a SCPI Server (Standard Commands for Programmable Instruments) which can be used to access the measured values with a sample rate of 10 Hz and additional information from the network. The different OPC UA Servers and Client, as well as the Data Storage are each running on identical B&R Automation PC 910 industrial PCs (IPCs) with an Intel Core i7-3615QE quad-core CPU running at 2.30 GHz. Both IPCs are equipped with i210 network cards from Intel and are connected via a 1 Gbps link. The computers operate with a real-time capable Preempt-RT Linux Kernel.

V. EVALUATION

To evaluate the software-defined testing facility we wanted to determine whether this approach and facility is fundamentally suitable for component testing. To examine this requirement a tensile test was selected, which is a classical case study for material testing. This tensile test is performed on two different test setups with almost identical boundary conditions, first on a typical universal testing machine (Zwick-/Roell Zmart.Pro Z1464) and second in the robot-based testing facility. The standardized testing procedure starts with the preparation phase (cf. Section III Figure 1). In order to test a wide stress-strain range, three different materials for the tensile specimen were chosen, which represent the component: steel (St 12), aluminum (1050-H16) and polypropylene (PPH) with the following dimensions: 135 x 12.5 x 3 mm^3 (length, width and thickness) for steel / aluminum and 170 x 10 x 4 mm^3 for polymer. In such a standardized tensile test, the specimen is loaded at a very low speed to guarantee a quasi-static loading, in one direction (tensile direction) without applying any pre-load until the component fails. This standard procedure also specifies the clamping points and loading points. This information was used in the next step to define the robot testing motion, as a load vector in one direction with absolute positioning as regulation mode. The termination criterion for this motion is the fracture of the specimen. The sequence of the motion execution is given by only one test motion and a simple position hold as a departure movement. After that the component placement was carried out with the help of the mixed reality commissioning tool. This tool is used to ensure that the robot can apply the necessary forces or torques at a given position. The forces are given by the load limits of the tensile specimen and are in this case at a given maximum of 16 kN. The final test setup in the robot-assisted test facility is

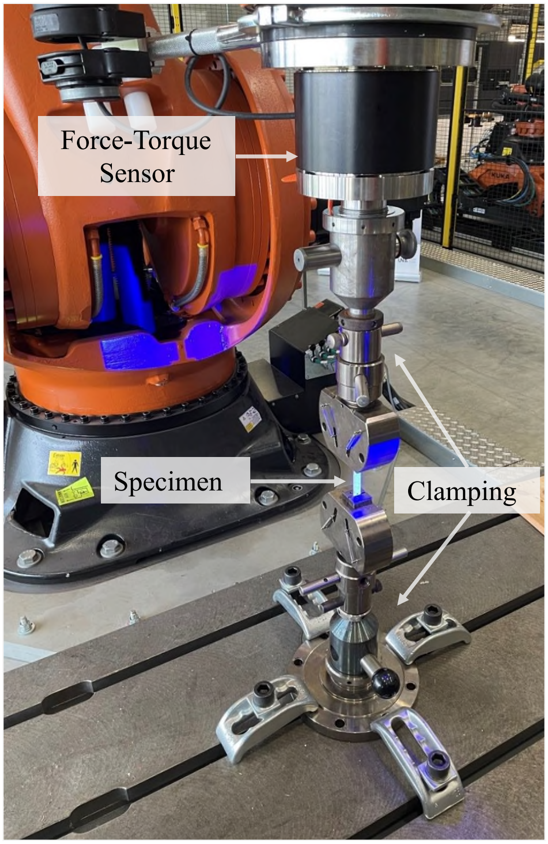

Fig. 6: Test setup for the tensile tests: Attachment of the clamping device (with clamped tensile specimen) between the clamping field (bottom) and the force-torque sensor on the robot (top).

illustrated in Figure 6 and consists of a robot with clamping jaws as end effector and a corresponding counterpart on the clamping field. The test object is inserted between the two clamping devices. As measuring device a F/T sensor was chosen to detect the fracture of the specimen and to record the forces and torques acting on the component. The ATOS5 was used as a second sensor in order to measure the specimen displacements. The hardware specifications were described in more detail in the previous chapter. To make the specimen evaluable for digital image correlation a speckle pattern was applied to its surface. This completes the preparation phase, as simulation was dispensed. In the next phase the motions were executed until the specimen broke, the data from the F/T sensor and the ATOS5 were aggregated and recorded. Finally, the post-processing phase was started with the data evaluation and in order to compare the results in the following part, the same tests were carried out on the standard Zmart.Pro testing machine. The test setup of the Zmart.Pro test machine is similar, except that a linear actuator is used instead of a robot. In addition, the ATOS5 digital image correlation system described in Section IV was used to measure the displacement fields. At first this strain motion was performed as a standard linear robot motion with standard KUKA control and the internal positioning system. By performing this simple standard tensile test different kind of problems were discovered that had to be solved. The first problem that occurred was triggered by the slow velocities, which are predefined in standard material or component tests [22]. Due to the slow acceleration curves of the linear motion the desired constant velocity of 6 mm/min in this case could only be reached extremely slowly and ultimately led to a failure of the KUKA robot controller. But the goal was to reach and maintain the test velocity as quickly as possible, which was not possible with this kind of standard motion control. Furthermore, the internal positioning of the robot is too inaccurate to control the motion and to implement the abort criteria. This is caused by the intrinsic deformation while the robot is being loaded, e.g. gear backlash or material deformation. In this test case it is important that the specimen loaded only orthogonally, i.e. in the direction of tension, and that no transverse forces occur. This cannot be guaranteed due to the imprecise absolute positioning of the internal control, as deviations up to half a centimeter for the absolute position of the robot were recorded here. We have solved these problems by introducing new types of motions (see III), which on the one hand allow more complex load cases, and on the other hand enable a deeper integration in the control system to compensate the deviation with the aid of external sensors, e.g. F/T sensors or any camera based sensor system. This integration is enabled by the proposed architectural concept, as the integration of these is significantly facilitated by standardized interfaces. In this use case the control component can now execute the testing motion in order to achieve the constant testing motion velocity. The robot was controlled with the help of the robot sensor interface (RSI), which is a technology package developed by KUKA and serves as a universal interface for KUKA Robots by enabling fine-tuning of predefined robot motions with live sensor data [23]. This interface was encapsulated with the help of an OPC UA server and connected to the control component via the ethernet based middleware. The control component was also connected to additional sensors in order to be able to compensate the previously mentioned deviations. Since the velocities for material tests are very low there was no need to implement a velocity curve. The data fusion of the F/T sensor and the ATOS5 was also successful based on the comparison of the data fusion of the standard testing machine Zmart.Pro. In order to be able to state how exactly a robot can imitate these motions, more research is planned.

VI. CONCLUSIONS

In summary, it is basically possible to mimic the motion of a standard testing machine and thus use industrial robots for component testing by using this approach. In the context of destructive mechanical component testing a novel robot-based concept and facility was introduced. To define this domain fundamentally and ensure test reproducibility a standardized test procedure was proposed. This procedure consists of three main phases. The first, the preparation phase, serves mainly for requirements analysis and preparation for the execution of a robot-based component test. The main task in this phase, besides the component placement, is the modeling of the robot motions and the motion execution order. For this purpose, we first distinguished three different types of test motions and introduced an abstract concept, which defines each testing motion as a combination of load vectors and termination criteria. A new concept for the execution sequence order was proposed using the syntax of state machines. In the second, called execution phase, the actual component test is carried out. An architectural concept was presented to realize these motions as well as the sensor data handling. In the final phase called postprocessing, the storage of the accrued data with association to the corresponding testing motions and component takes place. This data can later be used to optimize the testing motions. Overall a new approach for component testing through software specialization of robots and other actuators was achieved which is not limited to a few select load cases and which at the same time enables a wide range of testing motions. As a first proof of concept a standardized tensile test was performed in the evaluation on the one hand with a classical universal testing machine and, on the other hand, with a robot. Within these tests, three different materials, steel, aluminum and polymer were evaluated. This comparison showed that a robot is basically capable of imitating testing motions of a standard testing machine. In future experiments, we plan to evaluate more complex testing motions especially with superimposed loads. Moreover we are working to perform even more complex testing scenarios, including multi robot and additional actuators with higher forces, which, for example, can exert a base load on the component to be tested if the robot cannot apply sufficient force. Furthermore, we want to investigate minimizing the intrinsic drawbacks of the robots with the help of external measuring systems, e.g. 3D-Cameras. Finally, we are investigating how the component testing motions can be simulated and how the simulation can be compared to or adapt the real motion execution.

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