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An all-in-one robotic platform for hybrid manufacturing of large volume parts

Francesco Crivelli¹, Valentin Baumann², Markus Steiner², Mark D'Urso², Philipp Schmid¹, Alexander Steinecker¹

¹ CSEM SA, Untere Gründlistrasse 1, 6055 Alpnach Dorf, Switzerland

² Hexagon Manufacturing Intelligence, Mönchmattweg 5, 5035 Unterentfelden, Switzerland
francesco.crivelli@csem.ch

Abstract. 3D printing offers many advantages over conventional machining and its applications in industrial manufacturing is growing. However, existing additive technologies present limitations in workspace volume, accuracy and surface quality. These limitations could be overcome by combining both additive and subtractive processes. Such hybrid approaches allow layer-by-layer construction, alternating fast and rough material deposition with machining steps, when the layer's geometry is finished. Despite its potential, the development and industrial application of hybrid machines is slow. Particularly, no systems exist for the construction of large parts. The project KRAKEN is well-situated in this context, aiming at the development of a novel, fully automated, all-in-one platform for large volume hybrid manufacturing. This powerful tool will not only combine additive with subtractive processes, but it will also include both metal and non-metal 3D printing, resulting in a completely new machine for the construction of large, multi-material parts. A control approach based on direct measurement of the end-effector position will allow a combination of large workspace (up to 20 m) and high manufacturing accuracy (tolerances <0.3 mm, surface roughness $R_a <0.1$ μm). This paper presents the preliminary steps toward the development of this robotic platform, focusing on the use of the real-time feedback of an absolute laser tracker to control motion and positioning of the manufacturing robot. The proposed control strategy is presented and discussed. Finally, the use of an Extended Kalman Filter to fuse the laser measurement with the robot position sensors is presented and discussed based on offline evaluation.

Keywords: Hybrid manufacturing, large parts, multi-material, all-in-one machine, robotic manufacturing, extended Kalman filter.

1 Introduction

Additive Manufacturing (AM) processes consist of constructing objects directly from their 3D model by joining material layer by layer. These approaches present interesting advantages such as rapid prototyping and design freedom, and allow very complex and enclosed structures which are otherwise highly difficult or impossible to

build with traditional machining [1]. Currently, these technologies find many applications ranging from industrial production to individual consumer. Since 2003, part production based on AM has increased from 3.9% to 34.7% of all product and service revenues [2].

Today, at the industrial level AM machines exist which are able to produce parts up to 1 m³ in polymer material (BIGREP One, Fortus 900mc, Object1000 Plus), and even bigger volumes are reachable using sand casting (ExOne Exerial, Voxeljet VX4000), clay (WASP BigDelta) or metal (Xline2000, EOS M400, SML500HL, RPM Innovation, Norks Titanium RPDTM, SCIAKY). However, as larger parts are required, current technology shows its limitations. Most available AM machines have a limited construction volume due to process requirements (e.g. powder bed), inert gas or vacuum (e.g. laser or electron beam), or safety requirements (e.g. laser containment). In the future metal-based AM is expected to exceed polymeric-based processes in market size and growth [3]. Today, several metal-based AM technologies exist, however there is a lack regarding large volume production. In addition to production volume, present AM are limited in obtainable accuracy, surface quality, and uniformity of material properties. Today, the high quality and resolution required for applications in tight-tolerance and critical conditions can be reached only with considerable increase of cost-to-build-rate ratio, or it cannot be reached at all. This is the reason why most additive manufactured parts (both metal and thermosets) require post-processing to improve quality characteristics and/or relieve residual stresses.

Both volume and accuracy limitations can be overcome by combining AM with conventional machining processes (e.g. CNC) in workstations for hybrid additive and subtractive processing (WHASP) [4]. The capability of these hybrid systems to both add and subtract material in a concurrent and optimized manner allows construction of high quality parts within a single machine as well as addressing geometrical challenges (e.g. internal and overhanging features), reducing material wastage and tooling consumption.

Hybrid machines have been a fertile research field since the mid-late 1990s [5, 6], however the commercialisation of this approaches has been slow. Particularly, no real solutions exist for constructions of large volume parts yet. Today, the development of commercial hybrid manufacturing is accelerating. In the future, reconfiguration and responsiveness are suggested to play a fundamental role in the manufacturing economy, which will move away from production lines toward single all-in-one machines able to transform raw materials into finished products. This is well aligned with the WHASP approach.

The European project KRAKEN is well-situated in this context, aiming to develop an all-in-one hybrid-manufacturing machine for customized design, production, repair, and quality control of medium and large parts [7]. In addition to different manufacturing processes, this robotic platform will allow combination of metal and non-metal structures, representing a considerable improvement with respect to the current large size products manufacturing. The project proposes a further development of the MEGAROB system, a platform for high accuracy machining of large parts (up to 20x6x3 m) developed using an industrial robot mounted on a crane [8]. Analogously to

this previous project, the novelty of the proposed approach is controlling robot positioning and motion based on the direct measurement of the robot end-effector pose (i.e. position and orientation) provided in real-time by an absolute laser tracker. Including real-time measurement of the absolute end-effector pose in the motion control loop allows compensation of the intrinsically limited absolute accuracy of both the crane and the robot. Using an absolute laser tracker has been shown to be effective in improving absolute accuracy of industrial manipulators in presence of low stiffness and unmodeled process forces [9, 10, 11]. The chosen approach will enable fulfilling both requirements of large manufacturing and tight-tolerance applications, with an affordable machine based on standard industrial components. With respect to existing machines which are constrained by limited workspace, accuracy performance, and costs that are directly dependent on mechanical components (e.g. actuated axes), this project proposes a flexible solution that can be easily adapted to desired workspace size and logistical configurations, with minor impact on functions and costs.

2 The Setup

2.1 Manufacturing approach

The proposed machine will allow production and reparation of middle and large parts with dimensional tolerances below 0.3 mm and surface roughness below $Ra\ 0,1\ \mu\text{m}$. The manufacturing concept is based on a layer-by-layer additive/subtractive alternating task [5, 6]. Step after step, the material deposited during the additive process is machined in order to correct geometrical characteristics. This allows high manufacturing accuracy, also for large parts up to 20 m, as well as releasing the stress in the 3D printed structures. Furthermore, this approach enables construction of complex geometries and enclosed structure that are not feasible with existing conventional methods.

The layer by layer approach will include a geometry inspection step, where the actual execution of the manufacturing task and the accuracy of the constructed part are monitored in an automated manner using a high-resolution metrology device (T-SCAN, section 2.3) mounted on the robot end-effector. This allows direct identification and immediate reparation of eventual errors and deviations from the desired accuracy. Such in-process intervention prevents a full part to be rejected and, consequently, dramatically reduces wasted time and material. A concluding grinding and polishing step allows production of final parts with high quality surfaces (roughness $< Ra\ 0.1\ \mu\text{m}$).

The robot control system is based on an absolute laser tracker providing measurement of the robot end-effector's absolute pose (Cartesian position and orientation) in real-time. The direct measurement of the end-effector pose is used in the control-loop in order to compensate positioning and motion errors and achieve the desired high geometrical accuracy. Furthermore, the laser tracker will be used to automatize robot calibration processes as well as the identification of geometrical characteristics and localization of cell components and manufacturing workspace.

2.2 Robotic platform

The machine is based on the same robotic structure developed in [5], which consists in an industrial 6 degrees-of-freedom (DoF) anthropomorphic manipulator (NJ130, Comau S. p. A., TO, I) mounted upside down on a three-axes overhead crane (**Fig. 1**).

The crane structure measures 24x6x5 m and allows a workspace of approximately 22 m length, 4 m width, and 2 m height. The two horizontal axes are driven by motors and brakes directly acting on the moving wheels of the crane. The vertical axis moves the robot up and down using an actuated rack and pinion system, guided through two sliders, and supported by four electrically controlled pneumatic cylinders. The crane motion is controlled in open-loop and no external position sensors are used.

The robot supports payload up to 130 kg, has a maximum horizontal reach of 2.980 m allowing flexible and effective handling of the different tools required for hybrid manufacturing process. With a repeatability of 0.07 mm, the robot guarantees the high positioning accuracy required for tight-tolerances applications and high-quality manufacturing.



Fig. 1. Prototype system with CSEM control and Leica tracking system (installation at AITIIP, Zaragoza, Spain).

2.3 Absolute Laser Tracker

The Leica Absolute Tracker AT960 is a robust, all-in-one laser tracker offering high-speed dynamic measurement as standard. It is a complete solution for 6 DoF probing, scanning and automated inspection as well as reflector measurement.

The AT960 features wireless communication and a battery operation option. The Absolute Interferometer (AIFM) enables accurate high-speed measurement (**Table 1**) to a moving target while the PowerLock function ensures an interrupted beam is instantly re-established without user intervention, reducing operator workload and training requirements. Intuitive touch-screen controls minimize the potential for user error, saving time, effort and money. Check and compensation architecture means basic adjustments can be made in the field, while robust design guarantees on-specification operations with minimal calibration and servicing.

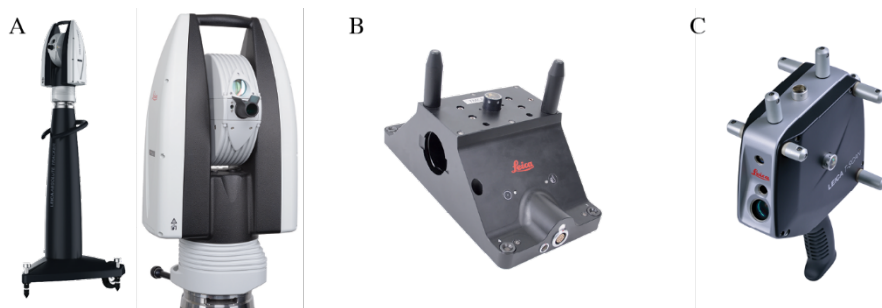


Fig. 2. A) Leica Absolute Laser Tracker AT960. B) T-MAC. C) T-SCAN.

Real-Time Interface. When combined with the Real-Time Feature Pack, the Leica Absolute Tracker AT960 evolves into a laser tracker solution that meets the deterministic measurement data-delivery requirements of high-end automated installations. Built on the industry-proven EtherCAT protocol, it enables the delivery of 6 DoF measurement data with accurate timestamps at an output rate of up to 1000 Hertz. Known as 7 DoF measurement data, this enables real-time machine control even with highly-dynamic robotic setups.

The fully automated measuring system makes measurement processes more time- and cost-efficient than ever before. The process accuracy is no longer limited by the positioning device. The unparalleled accuracies of the 6 DoF Leica Absolute Tracker AT960 can be applied to any robotic positioning system, turning it from an ordinary robot into an incredibly accurate metrology device. With a Leica T-Scan or a Leica T-Mac equipped with a tactile or optical probe mounted on a robot, the Leica Absolute Tracker AT960 is the core of a completely automatic coordinate measuring installation.

T-MAC. The Leica T-Mac (Tracker-Machine control sensor) is the next-generation 6DoF tracking device for automated applications. It answers the needs of a growing number of tracker customers who have either modified the existing Leica T-Probe for automated measurement applications or have expressed interest in doing so.

The Leica T-Mac is an off-the-shelf solution that can be custom-tailored to the needs of a specific application. For example, when needed, an interface for precise tool exchange units can be included.

T-SCAN 5. The combination of Leica T-Scan 5 and Leica Absolute Tracker offers the perfect match to ensure the capture of hundreds of millions of accurate points on virtually any surface, from highly reflective to matte black, even carbon fiber, all without any special preparation. The higher scan rates allow ideal feature recognition, smaller detail detection and much quicker scanning at an approved quality level on all surfaces and colours. The user’s scanning experience is enhanced with a dual color guide light and acoustic feedback. The Leica T-Scan 5 is also best qualified for automation and robotic applications, where inspection processes can benefit from maximum laser tracking and machine performance.

Table 1. Accuracy of the Leica Absolute Laser Tracker AT960 and related accessories.

Accuracy values	
Reflector*	$U_{(x,y,z)} = \pm 15 \mu\text{m} + 6 \mu\text{m/m}$
AIFM Absolute Distance Performance	$\pm 0.5 \mu\text{m/m}$
Absolute Angular Performance	$\pm 15 \mu\text{m} + 6 \mu\text{m/m}$
Dynamic Lock-on	$\pm 10 \mu\text{m}$
Orient to Gravity (OTG)	$U_{Z(OTG)} = \pm 15 \mu\text{m} + 8 \mu\text{m/m}$
Leica T-Scan 5	$U_L = \pm 60 \mu\text{m} / 210\,000 \text{ points/s}$
Leica T-Mac**	$15 \mu\text{m} + 6 \mu\text{m/m}$
Typical Rotation Accuracy	$\pm 0.01^\circ$
Accuracy of Timestamp	$<5 \mu\text{s}$

*All accuracies specified as Maximum Permissible Errors (MPE) and calculated per ASME B89.4.19-2006 and ISO10360-10:2016 using precision Leica 1.5” Red Ring Reflectors at up to 60 m distance unless otherwise noted.

**All accuracies specified as Maximum Permissible Errors (MPE). Typical results are half of MPE.

2.4 System architecture

The main software runs on a regular windows-based desktop PC and allows the user to interact with the system. This high-level software allows bidirectional communication with each system component over TCP/IP communication protocol.

The manufacturing process is divided in steps. The crane moves the robot to the working position and the robot performs the manufacturing task for the specified working position. After the task is concluded, the robot is moved to the following working position, and the same procedure is repeated until the whole part is constructed.

During each task, the crane is maintained in a stationary position and the robot is guided along the desired trajectory. The robot motion is controlled through a Comau C4G Open system. The “open” feature offered by this interface allows partial or complete modification of the standard control approach by integrating an external controller (**Fig. 3**). Such additional external controller has been implemented on a regular desktop PC running Linux patched with RTAI extension, which guarantees real-time execution of the control algorithms. The external controller PC is interfaced with the C4G Open unit over RTNet at a frequency of 1 kHz.

The external controller completes the control action of the standard controller in order to compensate the deviation of the robot end-effector from reference position and orientation, given in an absolute coordinate frame (section 2.5). The 6D pose of the robot end-effector is measured and provided in real-time by the absolute laser tracker (section 2.3) at a frequency of 1 kHz over EtherCAT.

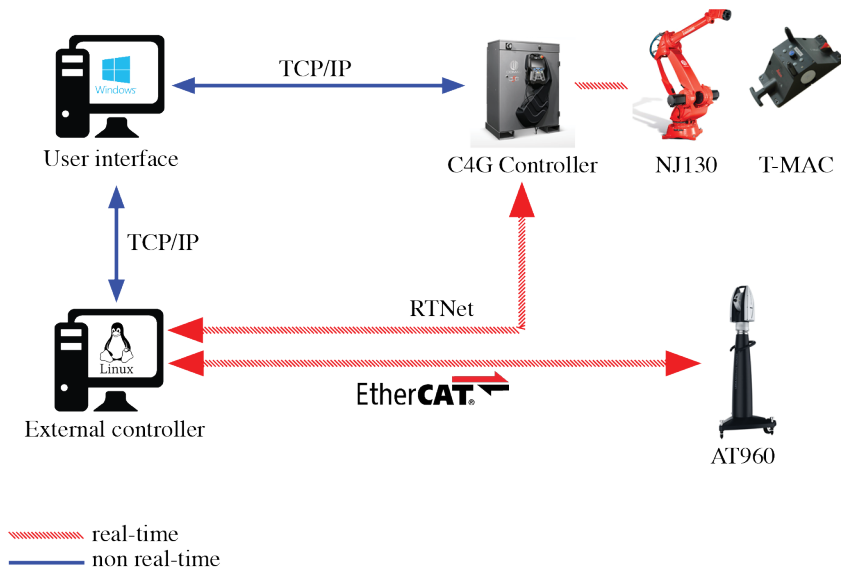


Fig. 3. System architecture.

2.5 Control approach

The robot controller is divided in two parts: the standard Comau controller and the external controller. The Comau controller is used to move the motor on the desired trajectory given in the robot coordinate frame. The controller includes customisable velocity and acceleration profiles, payload and weight compensation, kinematic and dynamic models of the robot, as well as low level closed-loop control of the robot motors. Robot kinematic is calculated based on the Denavit-Hartenberg convention [12].

The external controller is used to compensate: the deviation of the end-effector absolute pose from the desired trajectory as well as the deviation of the robot base from its ideal pose.

The position and orientation of the robot base with respect to the global coordinate frame (A_L^R) are obtained prior to the manufacturing task through least-squares estimation [13]. However, during operation the backlash and elasticity of the crane could cause a displacement of the robot base with respect to the ideal value. The external controller estimates the actual position of the robot base and the related coordinate transformation matrix ($A_R^{\hat{R}}$), based on the measured position of the robot joints, the measured Cartesian position of the end-effector, and the robot's kinematics model. The

corrected pose of the robot base is then used to recalculate the reference trajectory in the actual robot coordinate frame and improve the absolute accuracy of the system.

The difference between reference and measured end-effector pose in global coordinate is transformed into the actual robot coordinate frame, transformed to the joint space through inverse kinematics and fed to a linear PID controller. The resulting value is added to the control input calculated by the Comau controller and sent to the motor controllers.

Observing the control loop of the end-effector absolute position, the Comau controller can be described as the model-based feedforward term (open-loop) and the external controller as the feedback controller term (closed-loop).

An Extended Kalman Filter (*EKF*) [14, 15] has been implemented to improve the estimation of the Cartesian position of the robot end-effector based on the laser measurement, the speed of the robot joints, and the physical model of the system (section 3.2).

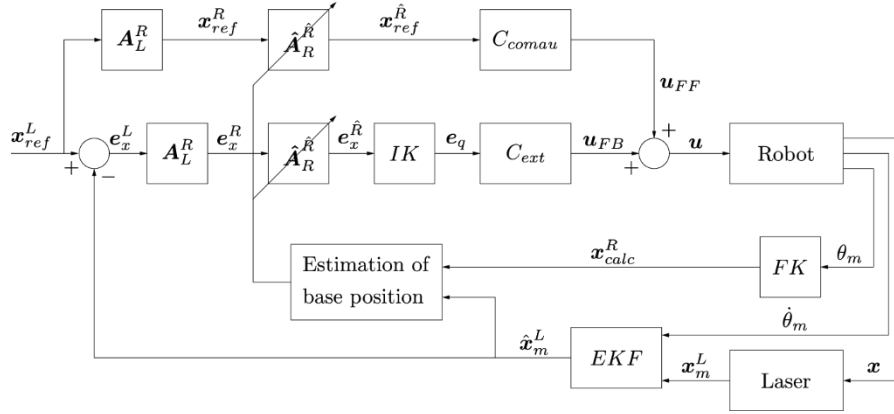


Fig. 4. Flow chart of the proposed control strategy. A_1^2 = homogeneous transformation matrix from 1 to 2; *FK* = forward kinematics; *IK* = inverse kinematics; *C* = controller. *Indexes*: *ref* = reference; *m* = measured; *calc* = calculated. *Coordinate frames*: *L* = laser (global); *R* = robot; \hat{R} = robot with base displacement correction; x, \mathbf{x} = Cartesian space; q, θ = joint space.

3 Preliminary Results and Discussion

3.1 Control Approach

A first version of the external controller was implemented and evaluated on a reduced setup of the KRAKEN system [16]. The reduced setup includes a 6 DoF industrial manipulator (NS12-1.85, Comau S. p. A., TO, I), which is a slightly smaller version of the robot used in the original system. The robot is mounted on a linear rail, which allows testing the performance of the motion controller in presence of robot base displacement (both desired and undesired). As for the original system, the 6D pose of the robot end-effector is measured with an absolute laser tracker and the same system architecture presented in (section 2.3) is used. The accuracy of the robot, calculated as the absolute

position error with respect to the reference trajectory, was evaluated in both free space motion and during milling (8.5 mm depth, medium-density fiberboard wood). The tests showed that even in presence of artificial disturbance of the robot base position (3 mm/s in random direction) the external controller allowed to keep the absolute error below 0.3 mm in free space motion and below 0.6 mm during milling [16]. The results show the feasibility of the control approach and the effectiveness of the external controller in improving the positioning and motion performance of the industrial robot (**Fig. 5**).

However, the implemented strategy was effective only for very slow movements (15 mm/s). Differently from the controller implemented in [16], the strategy described in this paper (section 2.5) will allow the external controller to directly act on the control input and not only on the reference point fed to the Comau controller. Additionally, the low-pass filters used in [16] to smooth the laser measurements have been replaced with a model based Extended Kalman Filter (section 3.2). These modifications will allow an increased bandwidth of the system that could improve the robot performance also at higher speed.

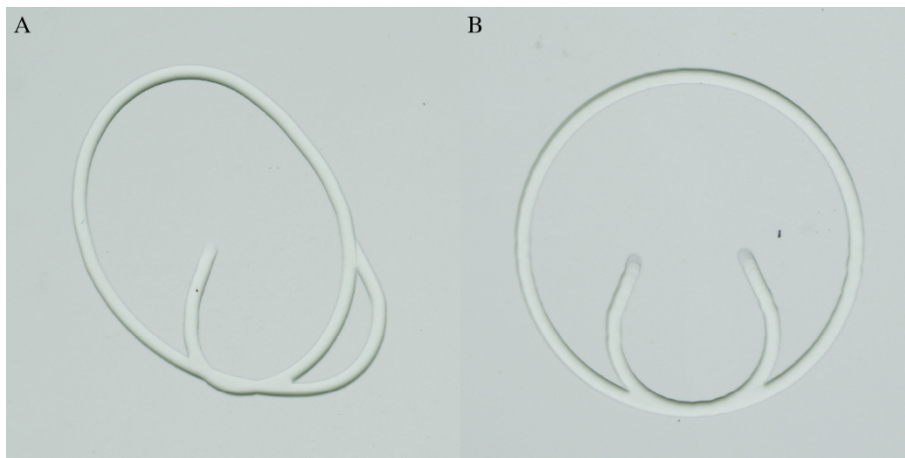


Fig. 5. Milling a circle with large disturbance in the robot base position. A) without external controller. B) with external controller.

3.2 Extended Kalman Filter

The control of the robot is based on the measurement of the robot's joint angular position provided by the C4G robot controller, and on the 6D pose of the robot end-effector provided by the laser tracker. While the encoders guarantee a highly precise and reliable measurement of the robot's joints position, the feedback provided by the laser tracker could present unexpected errors due to bad alignments between T-MAC (section 2.3) and laser tracker, laser beam/line of sight interruptions, or highly dynamic motions. In order to increase the robustness of the system in such critical situations a Kalman Filter was implemented. The Kalman approach allows fusing multiple sensors feedback into a reliable, real-time, model-based estimation of the robot state. These methods have

been widely used for multi-sensor fusion in order to enhance state estimation and control performance of robot manipulator [17, 18]. Particularly, Kalman filters are extensively applied to estimate the robot pose in task involving robot vision and vision-aided navigation [19]. Similarly, in this project a Kalman filter allows fusing absolute position and orientation measured by the laser tracker, with position and velocities directly measured on the robot joints. The system's state vector \mathbf{x}_k includes angular position, velocity, and acceleration of the robot joints. The state transition model is assumed to be a linear second-order system with no input, driven by random acceleration rate. The measurement \mathbf{z}_k includes end-effector position and orientation expressed in quaternion, and 3D Cartesian coordinate, and robot joint angular velocity (**Table 2**).

Table 2. Discrete transition model.

Transition model	
$\mathbf{x}_k = \mathbf{F} \mathbf{x}_{k-1} + \mathbf{w}_k$	$\mathbf{x}_k = [\theta_1, \dots, \theta_6, \dot{\theta}_1, \dots, \dot{\theta}_6, \dots, \ddot{\theta}_1, \dots, \ddot{\theta}_6]^T \in \mathbb{R}^{18}$
$\mathbf{z}_k = h(\mathbf{x}_{k-1}) + \mathbf{v}_k$	$\mathbf{z}_k = [X, Y, Z, q_1, q_2, q_3, q_4, \dot{\theta}_{1,m}, \dots, \dot{\theta}_{6,m}]^T \in \mathbb{R}^{13}$
	$\mathbf{M} = \begin{bmatrix} 0_{6,6} & \mathbf{I}_{6,6} & 0_{6,6} \\ 0_{6,6} & 0_{6,6} & \mathbf{I}_{6,6} \\ 0_{6,6} & 0_{6,6} & 0_{6,6} \end{bmatrix}$
	$\mathbf{F} = \mathbf{I} + T_s \mathbf{M} + \frac{T_s^2}{2} \mathbf{M}^2$

\mathbf{w}_k and \mathbf{v}_k are the process and observation noise with covariance matrix \mathbf{Q} and \mathbf{R} , respectively. $h(\cdot)$ is the forward kinematic function given in Cartesian position and quaternion orientation [12, 20]. While the state transition model is linear, the observation function $h(\cdot)$ is highly non-linear. Thus, an Extended Kalman Filter design was chosen, where the measurement residual is calculated using the non-linear function $h(\cdot)$, while the observation matrix \mathbf{H}_k is linearised around the current state estimation $\hat{\mathbf{x}}_{k|k-1}$ (**Table 3**).

Table 3. Extended Kalman Filter Algorithm

Prediction step	Update step
$\hat{\mathbf{x}}_{k k-1} = \mathbf{F} \hat{\mathbf{x}}_{k-1 k-1}$	$\mathbf{H}_k = \left. \frac{\partial h}{\partial \mathbf{x}} \right _{\hat{\mathbf{x}}_{k k-1}}$
$\mathbf{P}_{k k-1} = \mathbf{F} \mathbf{P}_{k-1 k-1} \mathbf{F}^T + \mathbf{Q}$	$\mathbf{K}_k = \mathbf{P}_{k k-1} \mathbf{H}_k^T (\mathbf{H}_k \mathbf{P}_{k k-1} \mathbf{H}_k^T + \mathbf{R})^{-1}$
	$\mathbf{y}_k = \mathbf{z}_k - h(\hat{\mathbf{x}}_{k k-1})$
	$\hat{\mathbf{x}}_{k k} = \begin{cases} \hat{\mathbf{x}}_{k k-1} + \mathbf{K}_k \mathbf{y}_k, & \text{if } \mathbf{z}_k \text{ reliable} \\ \hat{\mathbf{x}}_{k k-1}, & \text{otherwise} \end{cases}$
	$\mathbf{P}_{k k} = (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{P}_{k k-1}$

The implemented filter has been tested offline using MATLAB (R2017a, the MathWorks Inc., Natick (MA), USA), simulating arbitrary robot motion where the ideal end-effector pose has been artificially perturbed by adding Gaussian noise and missing data (**Fig. 6**). In the visualized example the 3D Cartesian deviation from respect to the ideal trajectory was reduced from 0.16(0.07) m (absolute error reported as $mean(standard\ deviation)$) to 0.07(0.03) m, while the orientation error calculated as the angle of the quaternion difference was reduced from 9.00(3.90) deg to 3.89(1.71) deg. This preliminary evaluation shows how the implemented algorithm is effective and robust in significantly improving the quality of the signal even in presence of 50% of randomly distributed missing values. In the next step the performance of the implemented approach will be evaluated on the real robot.

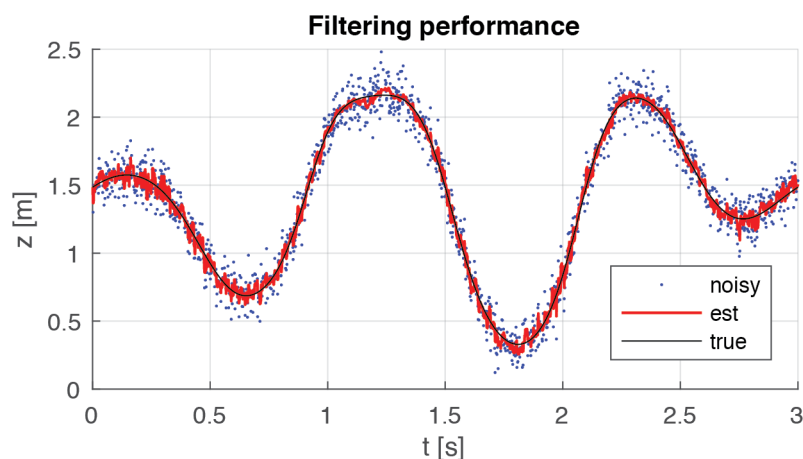


Fig. 6. EKF performance in offline evaluation. The plot visualizes end-effector z coordinate of a simulated trajectory. (*est*) shows the estimated pose calculated by the EKF for a simulated noisy measurement. The simulated measurement (*noisy*) was obtained by adding Gaussian noise and 50% of homogeneously distributed missed values to the ideal signal (*true*).

4 Conclusion and Outlook

This paper presents the preliminary steps towards the development of an all-in-one machine able to combine additive and subtractive manufacturing processes, as well as metal and non-metal material, into a novel and powerful tool which could represent a remarkable leap in industrial large volume manufacturing and prototyping.

Feasibility of the proposed approach has been proven for subtractive manufacturing and, currently, new control approaches are being investigated and tested in order to improve robot positioning and motion accuracy. Different manufacturing process will imply different control requirements: milling requires high position accuracy, finishing and polishing require constant interaction force between the tool and the part, while additive manufacturing requires constant dispenser velocity in order to guarantee ho-

mogeneous material deposition. Different control approaches are being studied and developed in order to meet those specific requirements and allow a successful integration of the desired manufacturing processes into this revolutionary hybrid manufacturing machine.

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