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MOBILE 3D SENSOR FOR DOCUMENTING MAINTENANCE PROCESSES OF LARGE COMPLEX STRUCTURES

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ABSTRACT

With the new handheld goSCOUT3D sensor system, the entire surface of complex industrial machinery spanning several meters can be captured three-dimensionally within a matter of minutes. In addition, a comprehensive photo collection is registered and precisely assigned to the corresponding 3D object points in one hybrid 2D/3D model. At the basis of the robust 3D digitization are the measuring principles of photogrammetric reconstruction using a high-resolution color camera and simultaneous localization and imaging using a tracking unit. Following image acquisition, the process leading to generation of the complete hybrid model is fully automated. Under continuous movement of the sensor head, up to six images per second and a total of up to several thousand images can be recorded. Those images are then aligned in 3D space and used to reconstruct the 3D model. Results regarding accuracy measurements are presented as well as application examples of digitized technical machinery under maintenance and inspection.

Index Terms – Optical 3D scanning, 3D modelling, photogrammetry, texture capturing, digital twin

1. INTRODUCTION

Industrial machinery, e. g. those used in production, propulsion, automotive or electricity sectors, consists of complex structures consisting of many components, such as tubes, pipes, connectors, etc. Regular inspection and maintenance are essential for reliable and safe operation over many years. The documentation of those works helps to identify and clarify later operational problems. Our goal was to develop a system for complete, fast, and accurate 3D capturing of complex machinery in industrial environments, including a comprehensive photo collection and, furthermore, a tool for inspecting the obtained digital model with all captured details. For best usability, the device used for data acquisition needed to be a lightweight, mobile sensor head for one-handed operation.

The typical goal of 3D object digitization is obtaining a virtual model of the object with true geometric surface as well as color and texture information. Furthermore, a tool for displaying this digital twin model with all captured details is needed. Two main challenges must be solved: (1) generating high-quality 3D surface scans including color and texture information and (2) correctly combining many single scans into a full 3D model with low scaling or position errors. The final inspection task is still done by human experts although automatic systems based on machine learning may be more important in the future.

Different technologies are used for optical object scanning. Photogrammetric systems are generally very accurate and simply built with one single camera [1]. However, they have limited allowance for three-dimensionally capturing areas in the object without texture or structure. Additional markers may be necessary or structured illumination may help to precisely capture homogeneous areas. Typically, if structured illumination (see [2]) is used, the measurement distance and field of view is limited. In addition, such systems consist of multiple camera and projection components, increasing overall size and weight.
All commercially available scanners (e.g. [3]) have their advantages and shortcomings. Favorable, they are lightweight and provide both high frame rate and spatial resolution, good accuracy, and a large field of view. However, the higher the resolution, the lower the generated 3D data rate and the smaller the field of view. Thus, compromises between the different requirements need to be made.
Industrial systems based on structured illumination with the purpose of accurate 3D surface measurement are more expensive and less mobile compared to photogrammetric scanners. Hence, their flexibility concerning immobile objects is limited. Processing the captured image data includes 3D point calculation, object surface modeling, 3D model generation, and fusion of existing model data with new scan data.
We decided to apply the photogrammetric principle in goSCOUT3D because it allows better usability by operators. Typical objects of interest in inspection and maintenance have sufficient texture to ignore that fundamental drawback. For the data processing, existing software tools can be used (e.g. “Agisoft Metashape” [4], “RealityCapture” [5], “Meshroom” [6], and “Colmap” [7]).
We developed the goSCOUT3D system optimized for mobile application at large industrial machinery and a process chain to support maintenance and inspection processes. In the following, we describe the specialties of our system, characterize its performance, and show some application examples.

2. THE 3D-SENSOR

The mobile sensor consists of a color camera, a ring light for illumination, a tracking camera, a control unit, and a touch screen. The power supply is realized by a rechargeable battery which is housed with the control unit separate from the handheld scanning unit. Batteries and control unit are connected to the scanning unit by one cable. They are carried in an additional shoulder bag. This reduces the weight of the handheld unit to approximately 1.3 kg. Control unit and battery together weigh about 1.0 kg. Figure 1 shows the front and backside of the scanning unit. The color camera is of type Baumer VCXG-204C with 20 MPix resolution and a frame rate of 6 fps. The tracking unit gathers data concerning position, orientation, and velocity of the sensor at approximately 150 Hz. The field of view is about 1 m² at a measurement distance of 1 m ± 0.3 m. The ground sampling distance is < 0.25 mm. The sensor head features a 5.5” touch screen for control and user guidance. The battery has a capacity allowing for several hours of scanner use.
The tracking unit is a low-power, stand-alone simultaneous localization and mapping (SLAM) device – the Intel® RealSense™ Tracking Camera T265. This device, which combines two fisheye cameras, an inertial measurement unit (IMU) and vision processing unit, provides a low-power, low-latency estimation of position and orientation (“pose”) of the goSCOUT3D sensor. Using these poses (IMU data), all captured camera photographs are robustly oriented in unknown environments without further markers or external tracking devices.
The scanner benefits from the availability of the pose data mainly in two ways: dramatic speed-up of the 3D reconstruction during the postprocessing phase after data acquisition, and user guidance and scanning support during the acquisition. The speed-up is achieved by

complementing each captured source image with the current pose. This serves as a starting solution for the computation of corresponding features and optimized sensor poses, eliminating many unnecessary 2D image-based computations that are deemed implausible due to non-overlapping views. Furthermore, redundancy due to images with only slight pose differences can be reduced by suppressing these. The quality of the input images can be ensured by encouraging the operator to avoid overly fast scanner movement to achieve sharp photos without motion blur. To this end, positional and angular velocities are used.

Figure 1: Front and backside of the scanning unit for one-handed operation.

User guidance, as a second benefit of the self-orientation, helps the operator already during the data acquisition phase to capture the object in question completely. By projecting the view frustums' respective focal plane (in the global coordinate system obtained by the self-orientation) of previously successfully acquired images into the sensor's live image at the current pose, the operator can easily estimate scanning progress and remaining uncovered object areas. Furthermore, by evaluating the orientation of the scanner, the system can help the user to capture each part of the object from multiple angles, increasing object coverage and reconstruction quality even more. Lastly, user input at the time of capture of a particular object detail, e.g., a fault report or observed peculiarity, can directly be linked to that object detail in the generated 3D model, thus alleviating user input efforts in subsequent reporting tasks.

3. DATA GENERATION PROCESS

The process of 3D data generation is split into acquisition with the scanning unit and, afterwards, the 3D reconstruction on a workstation. At acquisition, the scanning unit continuously records up to six camera images per second while the user guides it over the object's surface. Advice regarding brightness and motion speed are given to avoid images of poor quality. The ring light typically illuminates the scene. The exposure time is set to 2.5 ms to reduce image blur caused by motion during exposure.

The tracking unit estimates its motion in its own 3D coordinate system and provides a trajectory of the sensor's temporally changing poses at a frame rate of approximately 150 Hz. Both coordinate systems (from color camera and tracking unit) are linked, and the data are stored in a common world coordinate system (WCS). Using time stamps, matching pose data and camera images are identified. All camera images of acceptable quality, and pose data are committed afterwards to the reconstruction software which computes the 3D model and makes it available for monitoring and inspection tasks. Reconstruction of the 3D model is realized according to the well-known photogrammetric principle (see, e.g., [1], [8], [9]). It is performed in three major steps: alignment, 3D mesh generation, and texture bending.

In the first step, the accurate alignment of all camera poses is determined. Generally, this does not require any additional information beside the images itself. Image texture features are extracted and matched within the series. Then, camera poses are calculated by bundle block adjustment. This requires an extended processing time, if the object is complex and hundreds or thousands of images are necessary for complete capturing. In our scanner this elaborate processing is sped up by using IMU data. Only images with nearby positions are selected for image feature matching and, furthermore, the IMU poses give an initial solution for the bundle block adjustment. The alignment step runs significantly faster by using the IMU data. Certain optical parameters (e.g., focal length) are provided as well.

In the second step, the full 3D mesh model of the object is reconstructed. At this step only a subset of the complete image series is used, because of the large redundancy of the image contents. During mesh generation, depth maps are calculated using a multi-view stereo method. Up to 16 neighboring images are used for distance calculation and averaging, resulting in a depth map for each selected image. All depth maps are used to build the full 3D mesh model of the object.

In the third step, the texture is created as layer on the mesh model. The texture is calculated by blending images pertaining to a certain surface point. The texture layer can have a significantly larger resolution than the mesh itself. Because the camera poses in relation to the 3D model are known, it is also possible to return from the mesh model to the original images for displaying or inspection purposes. All these steps are accomplished in a completely automated workflow using the commercial photogrammetry software “Agisoft Metashape” (AS) [4].

4. TOOLS FOR USER GUIDANCE

In order to optimally support the user during the process of data capturing a user-friendly GUI (see Fig. 2) and some special additional software tools were implemented.

The device offers various user-controlled adjustments for image processing. Users can select pre-set brightness and contrast settings of the recording color camera, enabling customization and optimization of visual data. Additionally, the device allows for digital zooming of the image stream, enhancing the level of detail shown during recording.

The device also incorporates several warning systems to enhance user experience and data quality. It is equipped with a mechanism to alert the user if moving too quickly, ensuring reliably tracked imagery for later reconstruction. Furthermore, if tracking confidence of the device is low, the user is notified, giving them the opportunity to regain tracking confidence and maintain accurate data recording. Similarly, the device can indicate which image regions are over or underexposed, alerting the user to ensure proper exposure settings.

For data management, the device provides the option to export recorded data to a USB drive, facilitating data transfer and backup. Users can also delete unwanted recorded data to free up storage space on the device.

To guarantee the acquisition of the entire object surface, the device includes a unique feature that overlays the history of the captured images onto the object. This colored overlay represents parts of the object already recorded (see fig. 2 right). This assists the user on-site to identify potential gaps in the digitization and to keep a certain level of overlap between the images required for photogrammetric 3D reconstruction.

The device's tracking unit provides 3D location and orientation data. Using this information, the device calculates past camera view "cones" (frustums) with respect to the current sensor position and orientation. By intersecting these frustums with a plane at a fixed distance of one meter, a rectangle overlay is created onto the image stream. As the device moves, the rectangles appear to adhere to the imaged object, rotating and translating along with it. The overlay selectively shows these rectangles based on distance and direction, ignoring views taken from near-perpendicular and opposite views of the object. Lastly, the device offers flexibility in settings customization. Users can adjust parameters such as screen size, default values, exposure warning, connection to the ring light, and the transparency, size, and reset functionality of the history overlay.

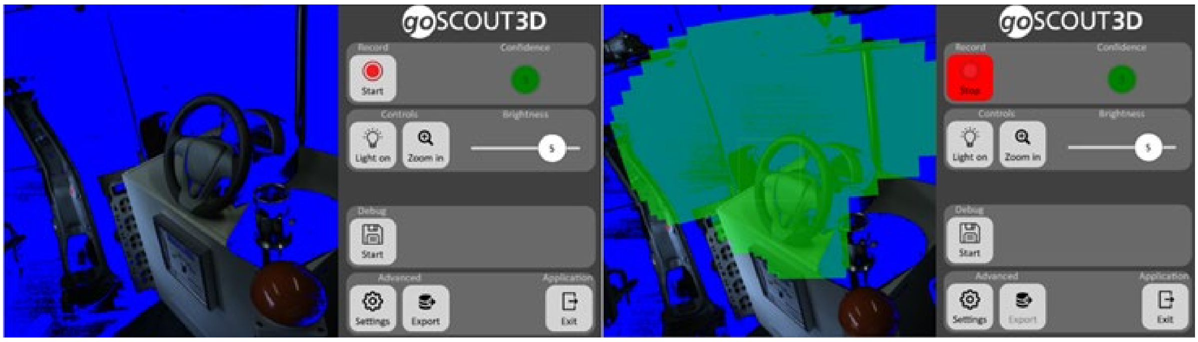

Figure 2: Main view of the user interface. Blue regions indicate underexposure (left). During record mode, an overlay is shown of previously imaged parts of the object using green rectangles (right).

An important indicator for the practicability of the scanning system is the processing time required to generate and display the object model. The main parameter responsible for the processing time is the number of recorded images. This depends, of course, on the size of the object and its complexity. It can be stated that the 3D model generation process is completely automated and takes about 20 minutes per 1,000 images on a workstation. In a quick preview mode, the complete processing time is considerably sped up by a reduced detail level.
In addition to the scanning unit GUI, a workstation software tool for presentation, inspection, and analysis of the obtained 3D models was developed. One key feature is a function that selects the best 2D-images of a selected 3D point on the model. The user selects points of interest in the model view (see fig. 3 left) by clicking and obtains the best 2D images connected with the corresponding object position (fig. 3 right). This allows maintenance workers and inspectors to assess photos of the point of interest which is more in accordance with their existing workflows.

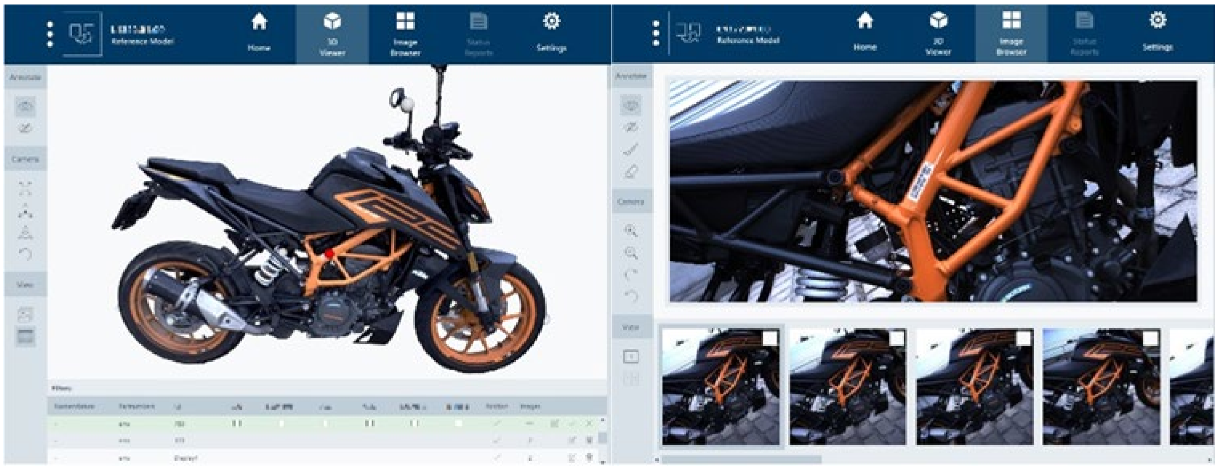

Figure 3: Model analysis software showing a recorded and completely modeled bike object (left) with selected position (red dot), and corresponding detailed views in the camera images (right).

5. EXPERIMENTS AND MEASUREMENT EXAMPLES

5.1 Accuracy measurements

In order to assess the obtained measurement values, experiments on measurement accuracy were carried out following the VDI/VDE guideline 2634 [10]. The experiments were performed in several sessions. The quality parameters probing error, sphere-spacing error, and flatness measurement error [10] were determined and analyzed. To perform the measurements according to [10] we used a ball-bar with spheres of approximately 100 mm diameter for sphere spacing error and probing error determination in one workflow. The spheres were measured previously using a coordinate measurement device "UNI-VIS 250" (by Mahr GmbH) as reference. The determined reference radius size was 49.591 mm, and the shape deviation was 8.8 µm for sphere S_1, and 49.590 mm (radius) and shape deviation 6.7 µm for sphere S_2.

For probing error determination, the spheres were placed in 16 different positions evenly distributed in the measurement volume (see fig. 4 left). The average value Δr_{av} of the radius deviation provides the result for the size measurement error, whereas the range of radial distance pv between measured points and a best-fit sphere characterizes the form parameter of the probing error. The results are: Δr_{av} = 2.02 mm ± 1.87 mm (size) and pv = 5.02 mm (shape).

The sphere-spacing error was determined from the distance between the spheres of the ball-bar. The calibrated sphere center-point distance is 995.721 mm. The mean length measurement deviation was 20.78 mm ± 0.74 mm in measurements of eight different positions in the measurement volume according to fig. 4 right.

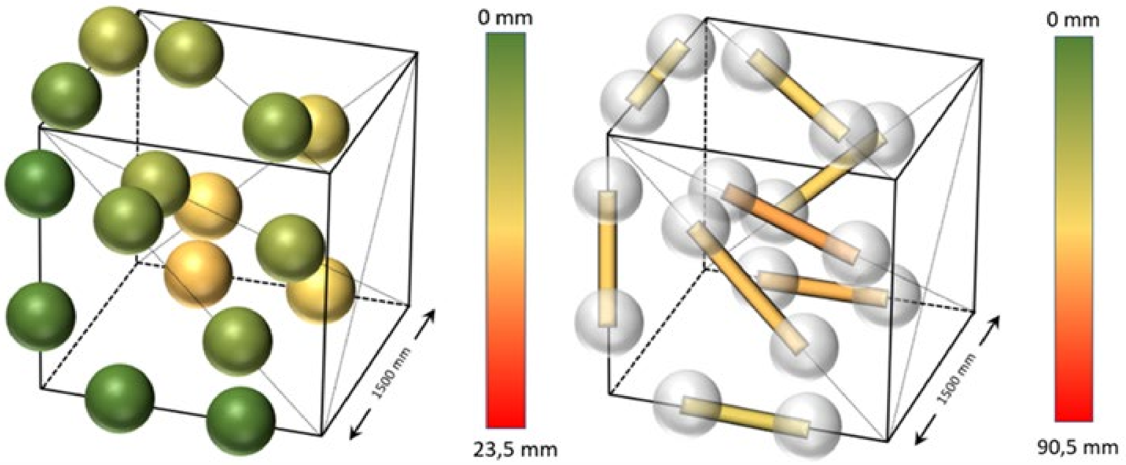

Figure 4: Distribution of the spheres of the ball-bars in the measurement volume for measurements of probing error (left) and sphere-spacing error (right). Colors represent the error magnitude.

Finally, flatness deviation was determined using an approximately plane surface of 1.5 x 1.5 m² size. The mean standard deviation of the point distances from a fitted plane was 0.86 mm ± 0.22 mm as the average value of six plane measurements at different positions. Each of the six plane measurements was repeated five times and averaged.

Additionally, the noise of the measured 3D points was estimated as the local standard deviation of the point distances to fitted spheres or planes, respectively. The noise at sphere measurements was 0.66 mm ± 0.45 mm, and at plane measurements 0.77 mm ± 0.14 mm.

To evaluate the stability of global scaling, ten repeated measurements were performed using two different ball-bars (see fig. 5). The coefficient of variation values cv_{dist} of the distance measurements can be used as an indicator for the stability of global scaling. In a second analysis, one ball-bar was taken as reference distance to calibrate the global scaling. The variation coefficient of the scaling factors between the two different ball bars vc_{12} indicates the random error of the determined scaling factor with explicit scaling calibration. According to the obtained values of cv_{dist1} = 2.1 %, cv_{dist2} = 2.1 %, and vc_{12} = 0.07% it can be concluded that accuracy of metric measurements can be improved by factor 30 if an object of known length is part of the scene. Average noise on the sphere surfaces was 0.9 mm (R = 37.5 mm) and 1.7 mm (R = 25 mm), respectively.

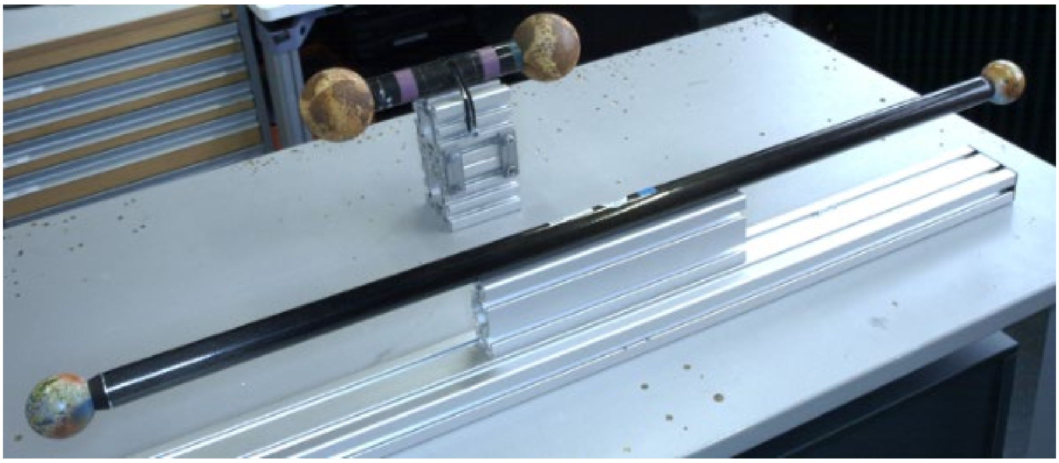

Figure 5: Ball-bars of different length (250 mm and 1000 mm, respectively) for scaling stability determination.

5.2 Application examples

A ventilation system on a roof was digitized to demonstrate the mobility and performance of goSCOUT3D in an outdoor environment. 1,668 images were acquired in less than ten minutes. Some images were automatically dropped where sensor movement was too fast. The reconstruction time to the final 3D model was 18 min and 24 s in standard and 6 min 3 s in quick preview mode. These calculation times were achieved using a PC workstation with Intel Core i9-10920X CPU with twelve cores and 24 logical processors and two Nvidia GeForce RTX 3080 GPUs. Figure 6 illustrates the scanning process, a general view of the complete object, and a detailed view which can be used for inspection documentation.

As a further measurement example, fig. 7 shows an optical high-speed 3D scanner consisting of stereo cameras, one pattern projector, a tripod and many data and power cables. Figure 8 shows the digital 3D model of a switchboard of an industrial computed tomography system.

6. DISCUSSION AND OUTLOOK

The presented measurement results and application examples show the high potential of the introduced scanning device goSCOUT3D for documentation of maintenance and inspection processes. Highly textured objects can be captured with outstanding attention to detail, supported by the comprehensive photo collection. Object zones with sparse texture are captured with lower 3D accuracy as well. However, correspondence to the recorded high resolution color images realizes high quality of the model view. The output is a digital twin of the object in a 2D/3D hybrid model.

Accuracy measurements according to the VDI/VDE guideline 2634 [10] showed that with additional scaling information high precision metric measurements are possible. If no exact scaling is available, errors in metric measurements up to 5% must be accepted. This uncertainty is due to the limited accuracy of the tracking camera. However, the average values of approximately 2% deviation in length and size measurements and outliers up to 5% are acceptable. Hence, if higher accuracy is necessary, fundamental measurement standards, such as ball-bars or other markers must be captured together with the actual measurement object. This might be necessary for certain objects under inspection.

Figure 6: Scanning process (top left), 3D model view (top right), detailed views of potential defects (bottom left), and trajectory of camera positions (bottom right).

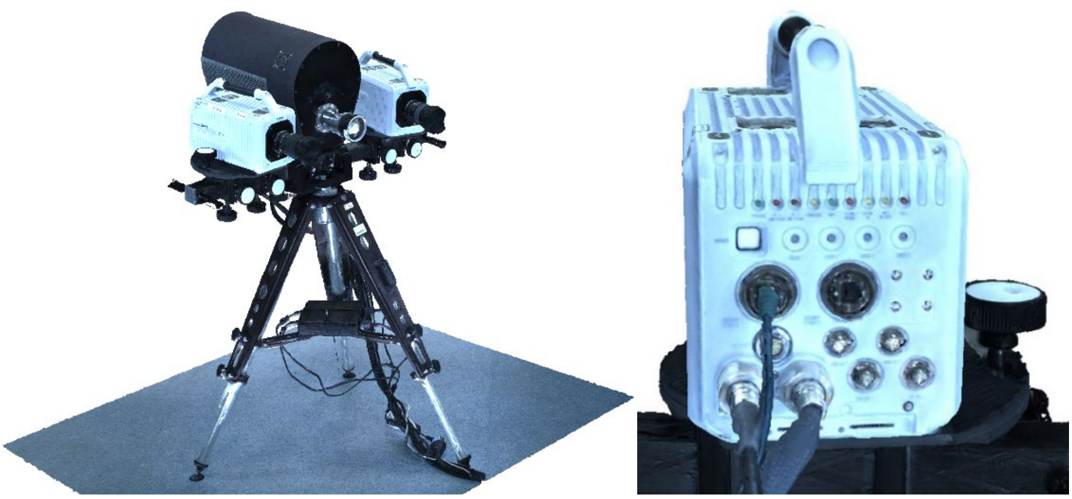

Figure 7: Digitized optical high-speed 3D scanner (left), detailed backside view of one of the modeled cameras (right).

Besides digitization of industrial machinery, the goSCOUT3D scanner system is suitable for different tasks, where complete 3D models of complex object must be generated.
Future work will address a further reduction of the weight of the scanner and an improvement of the robustness of the measurements. Additionally, a reduction of the postprocessing time required to generate the complete 3D model, would be of high interest to the users of the system.

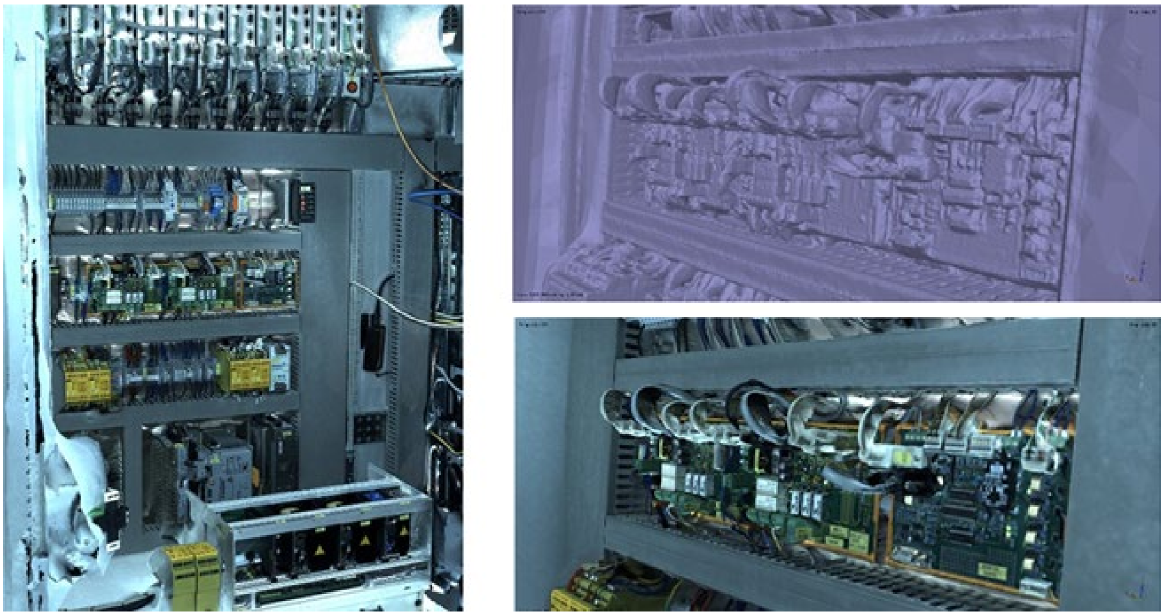

Figure 8: Digitized 3D model of a switchboard (left), detailed 3D surface view (top right), and mapped color information (bottom right).

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