Irma3D – An Intelligent Robot for Mapping Applications ⋆

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Abstract: Motivated by the increasing need of rapid characterization of environments in 3D, we designed a robot system that automates the work of an operator of terrestrial laser scanners. The built system enables to work without using special targets or markers and thus enables the surveyors to save more than 75% of the time spent in the field. Another impulse for developing the platform is the demand for a remote multi-sensor inspection tool. The robot is capable of surveying remote sites or danger areas, such as plants, underground mines, tunnels, caves, or channels. The results are precise, multi-modal digital 3D maps.
This paper presents the recently developed robot Irma3D, its hardware, the developed interconnected software modules, the associated sensor calibration methods and a few applications.

Keywords: Irma3D, mobile robots, 3D mapping, laser scanning, 3D point cloud coloring.

1. INTRODUCTION

As infrastructure degrades with age, regular inspection is necessary. Furthermore, as-built documentation must often regard in addition to geometry other sensor data. Over the past four years, we have developed the robot Irma3D which is capable to create digital 3D geometric models of environments in a tele-operated fashion. When the operation requires more than just a geometry assessment, multiple sensors are added. In addition to the laser scanner which gages the surrounding, calibrated cameras acquire color images or temperature information.

The challenge in automating remote inspection is to process all the sensor information. In addition to the hardware setup, the communication system must be able to record all relevant data. Furthermore, precise intrinsic and extrinsic calibration of the sensors is needed. This paper presents the hardware, middleware and user interface of the robot Irma3D. In two applications, we show how the calibrated sensors and SLAM (simultaneous localization and mapping) algorithms are used to build precise models for inspection.

2. THE ROBOT IRMA3D

2.1 Hardware

The Intelligent Robot for Mapping Applications in 3D (Irma3D) is a robotic mobile laser scanner that was developed for the purpose of exploring issues like registration and calibration in a mobile laser scanning scenario. Irma3D is a small, battery-powered, light weight, three wheeled vehicle. Irma3D and its components are depicted in Fig. 1. With a width of 52 cm it is small enough to pass through narrow doorways. The three-wheeled design allows for a high maneuverability such that it can rotate on the spot. These properties make Irma3D ideally suited for indoor environments. However, the high-powered electrical two-wheel drive powered by two 150 W DC Maxon motors with a top speed of about 2.2 m/s combined with the 26 cm wide pneumatic wheels also make it capable of operating in moderately challenging outdoor environments. The robot can be remote-controlled, either via a W-LAN connection or through a Logitech Wireless Gamepad F710 or similar devices. Irma3D can also be used in a fully autonomous mode. Once activated, Irma3D will attempt to explore its surroundings, up to some preset limits, and create a 3D map of the environment.

As a laser scanner platform, it can be used as a mobile laser scanner, i.e., acquiring range measurements while moving through the environment. Alternatively, the robot can remain on the spot to acquire a 3D point cloud. This type of static laser scanning is called stop-and-go scanning. It enables the creation of 3D models of the environment as detailed as with mobile laser scanning with higher precision. However, since the laser scanner is not operating while the robot is moving, more time is required in this mode to create equally large point clouds. This dual-use of Irma3D is made possible by the 3D terrestrial laser range finder it is equipped with. Without a 3D scanner that is able to rotate freely, Irma3D could not acquire 3D range images of its environment.

The robot Irma3D is a combination of several sensors, a mobile platform and a portable laptop for processing data

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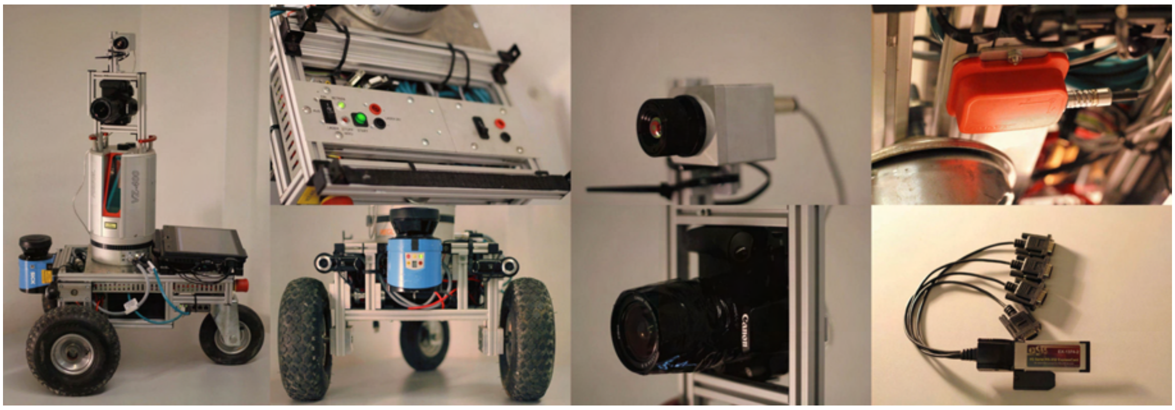

Fig. 1. Images of Irma3D. Left: Side view of Irma3D with all of its sensors and equipment. Top left: The control panel with switches for the two electric circuits, sockets for loading the batteries and the laptop mount. Bottom left: Front view of Irma3D. Two small digital cameras and a 2D laser scanner are attached to the front of the robot for easier navigation. Top middle: The thermal camera on top of the 3D laser scanner that is used to sense thermal properties of the environment. Bottom middle: A DSLR camera is mounted on the 3D laser scanner to provide color information for the point clouds. Top right: The IMU is mounted on the underside of the chassis next to the rear wheel to provide maximum shielding from the magnetic fields that are generated from the motors and the 3D laser scanner. Bottom right: An ExpressCard to RS-232 Adapter is used so that modern laptops without serial ports can interface with the Volksbot motor controller and the IMU device.

and controlling the robot itself. The chassis of the robot is a modified Volksbot RT 3. The Volksbot RT 3 has two front wheels. Each is actuated by an individual 150 W DC Maxon motor. The motors are powerful enough to move the robot at a maximum velocity of 2.2 m/s. The third wheel is in the back of the chassis and is swivel-mounted and thus completely passive as it follows the directions of the front wheels. The platform is powered by four 12 V 7.2 Ah Panasonic lead-acid batteries, two more than in the original design. The chassis has been modified to provide two electric circuits. In addition to extra wiring the modifications include additional elements to the control panel in the back of the Volksbot RT 3. The chassis has a variable laptop mount to fit any reasonably sized laptop. Currently Irma3D operates on a Samsung Q45 Aura laptop with an Intel Core 2 Duo T7100 and 4 Gb of RAM. The laptop mount has been situated such that the laptop will rest above the control elements of the chassis (see Fig. 1). Therefore, the emergency stop button has been moved to the rear of the platform to keep it accessible at all times. The physical dimensions of the Volksbot platform are 58 cm × 52 cm × 31.5 cm with a weight of about 25 kg. A large part of this weight is from the lead batteries, each contributing about 2.5 kg.

For navigation and obstacle avoidance, the robot is equipped with a SICK LMS 100. This 2D laser scanner is mounted facing forward at the front of the chassis acquiring 2D range scans at a rate of 50 Hz. To fully exploit the 270° field of view, the sensor head is positioned slightly above the chassis. The SICK LMS 100 scans with a resolution of 0.5° and a maximum effective range of about 20 m. To support a human operator when the robot is remotely controlled two small Logitech QuickCam Pro 9000 web cams are also attached to the front of the chassis. The motors of the Volksbot are equipped with rotary encoders to measure wheel rotations. This information is used to provide pose estimates of the robot via odometry. The pose estimates are improved using data from the Xsens MTi IMU device that is also attached to the robotic platform. The IMU is susceptible to magnetic interference and must be positioned away from strong magnetic fields to reduce erroneous sensor readings. The motors as well as the laser scanners generate magnetic fields. Therefore, the IMU is fixed to the rear and bottom of the chassis.

The central sensor of Irma3D is the 3D laser scanner VZ-400 by RIEGL Measurement GmbH. The scanner is mounted on top of the Volksbot RT 3 chassis. Attached to the top of the scanner is a Canon 1000D DSLR camera. After a 3D scan has been acquired the camera is used to acquire color information for the point cloud. A similar process is done using the Optris PI160 thermal camera which is also mounted on top of the VZ-400 to acquire information about the thermal properties of structures in the point cloud. All cameras on Irma3D are USB devices. With the addition of the Logitech Wireless Gamepad F710 for remotely controlling the robot this adds up to a total of 5 USB plugs that need to be connected. To reduce requirements on the laptop Irma3D is equipped with a USB hub. Both laser scanners transfer information via ethernet. To enable the laptop to connect to both devices at the same time, Irma3D is provided with a network switch. The Volksbot motor controller as well as the Xsens MTi communicate via RS232 serial ports. Since modern laptops are rarely equipped with an RS232 port, let alone two, a Delock PCMCIA to RS232 adapter is used for communication. The laptop supplies its own power via the laptop battery. All USB devices except the DSLR camera draw their power from the laptop. The network switch as well as all other sensors with the exception of the VZ-400 share a power supply with the Volksbot chassis in the form of two of the four lead batteries. The remaining two lead batteries are dedicated to the VZ-400, as it draws a similar amount of power to the rest of the system.

The VZ-400 is able to freely rotate around its vertical axis to acquire 3D scans even when the robot is not in motion.

The fastest rotation takes 6 s. At this speed each point cloud will contain about 750000 points. The minimum angular resolution of a range scan is 0.0024° in both directions, which equates to more than 6 billion points per scan. The scanner is capable of on-line Full Wave Transform, may record multiple distance measurements per laser beam and will return not only the range of each echo, but also its amplitude, deviation and a calibrated reflectance value. The amplitude and deviation refer to the parameters of the normal distribution that is fitted into each response. The deviation of a point is a measure for the certainty of the measurement. The amplitude is roughly equivalent to the intensity with which the laser beam was reflected. This value is similar to what other laser scanners return as reflectance, reflectivity or intensity. It should be noted that this is not a good measure of the reflection coefficient of a surface. The intensity of a signal is affected not only by the reflectance properties of the surface but also by the angle of incidence, the distance to the surface, the temperature and other atmospheric conditions. The VZ-400 also returns so-called calibrated relative reflectance values, which attempts to correct the influence of the distance to the surface.

2.2 Middleware

Fig. 2 gives an overview of the components, which are connected using LAN, USB, and RS232. Tele-operation is either realized using a a wireless gamepad or WLAN to a remote computer running the user interface.

ROS fuerte is used to connect all components. ROS provides the hardware abstraction, the device drivers, and the message-passing. The system is based on a graph architecture where processing takes place in so-called nodes that may receive, post and multiplex messages containing information about sensors, control, state, planning, actuators and others. It provides an operating system-like functionality on a heterogeneous computer cluster. This multi-computer architecture is exploited to build the user interface for tele-operating the robot from a remote computer.

A critical issue is time synchronization. Messages from the embedded Volksbot Motor Controller (VMC) are time-stamped when they arrive at the central Q45 notebook. The VMC is built using a C167 micro controller and processes odometry data and acts as a PID controller for the two wheels. Similarly, IMU sensor data, LMS100 scans and camera images are time stamped and processed by the notebook, whereas the time synchronization between the VZ-400 scanner and the ROS system is realized in a different manner. The RIEGL VZ-400 time stamps all data with its internal high-precise clock. In addition, a ROS node logs these VZ-400 time stamps. This enables the association between the VZ-400 timestamps and the ROS time using a search for closest timestamps.

2.3 User Interface

The challenge in tele-robotics is the precise control of a mobile robot, especially when the robot cannot be seen and observed directly. In this case, the computer interface represents some data of the robot and its surroundings. Human Robot Interaction (HRI) is then a special case of Human Computer Interaction (HCI), considering that the operator does not control a computer interface, but an expensive mobile robot.

To perform HRI, a Graphical User Interface (GUI) uses a combination of technologies and devices to produce an environment where the user interacts with the machine, performing tasks of gathering and passing information/commands. The most common combination of such elements in GUIs is the WIMP paradigm, i.e., windows, icons, menu, pointing device. Designing the architecture and temporal behavior of a GUI has a crucial role in software application programming. Its goal is to enhance the efficiency and ease of use for the underlying logical design of a stored program. Typically, the user interacts with information by manipulating visual widgets that allow for interactions appropriate to the kind of data they hold.

The GUI (cf. Fig. 3) is capable of displaying data provided by the robot sensors, such as 3D scans acquired by the VZ-400 laser scanner in a stop-scan-go-fashion, camera images delivered by the two Logitech web cams, and 2D scans taken by the 2D SICK LMS100 scanner. For tele-operating the robot the 2D laser scans are essential as they provide a local up-to-date map-like representation. Controlling the robot using camera images is in contrast to using 2D laser scans extremely hard as they have only a very narrow field of view. The best situation awareness is provided by the 3D point cloud, however, acquisition and data transfer over the wireless network requires some time.

3. APPLICATIONS

The applications of Irma3D concern mapping tasks using the VZ-400 scanner. Multiple 3D scans are necessary to digitalize environments without occlusions. To create a correct and consistent model, the scans have to be merged into one coordinate system. This process is called registration. If the localization of the robot with the scanner was precise, the registration could be done directly based on the robot pose. As relative self localization is erroneous the geometric structure of overlapping 3D scans has to be considered for registration.

Registration of 3D Scans. The following method for registration of point sets is part of many publications. The complete algorithm was invented in 1992 and can be found, e.g., in (Besl and McKay, 1992). The method is called *Iterative Closest Points (ICP) algorithm.* The procedure considers all six degrees of freedom. i.e., x, y, z coordinates and roll, pitch and yaw angles..

Given two independently acquired sets of 3D points, M ($|M| = N_m$) and D ($|D| = N_d$), which correspond to a single shape, we aim to find the transformation consisting of a rotation $\boldsymbol{R}$ and a translation $\boldsymbol{t}$ which minimizes the cost function

$$E(\boldsymbol{R}, \boldsymbol{t}) = \sum_{i=1}^{N_m} \sum_{j=1}^{N_d} w_{i,j} \left|\left|\boldsymbol{m}_i - (\boldsymbol{R}\boldsymbol{d}_j + \boldsymbol{t})\right|\right|^2 \quad (1)$$

$$\propto \frac{1}{N} \sum_{i=1}^{N} \left|\left|\boldsymbol{m}_i - (\boldsymbol{R}\boldsymbol{d}_i + \boldsymbol{t})\right|\right|^2 , \quad (2)$$

Fig. 2. System network. Components are connected by RS232, USB and LAN. Control is provided by a wireless joystick or a base station running an user interface.

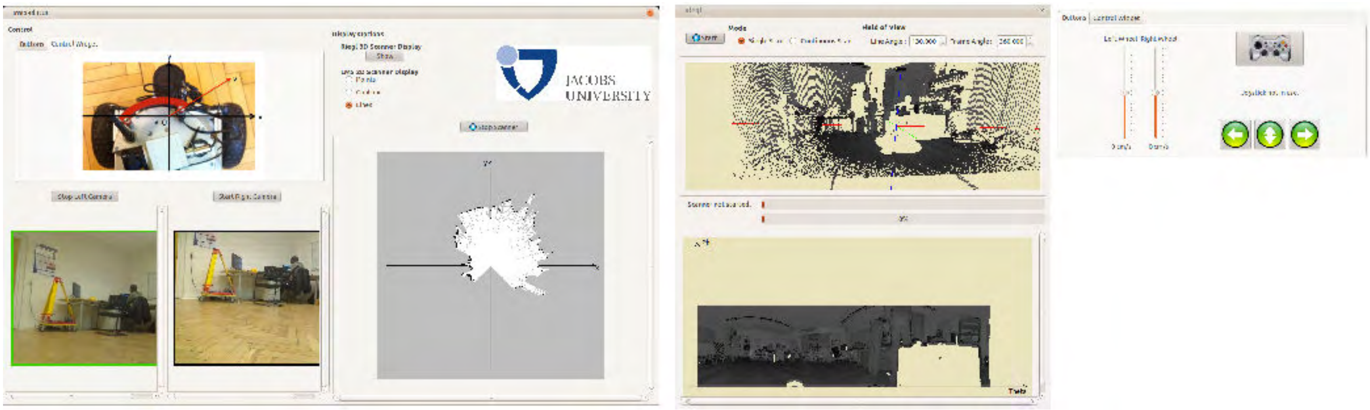

Fig. 3. User Interface of Irma3D. Left: Main window with control, camera images and 2D laser scans. Right: 3D laser scans viewed as 3D point cloud (above) and range image (below). Bottom: Robot control with buttons.

After inital registration of all acquired 3D point clouds with ICP, a bundle-adjustment like global relaxation is used for globally consistent 3D mapping with scan matching (Nüchter et al., 2010), which minimizes iteratively the error function:

$$E = \sum_{k,l} \sum_{i=1}^{N} ||\boldsymbol{R}_k \boldsymbol{m}_i + \boldsymbol{t}_l - (\boldsymbol{R}_l \boldsymbol{d}_i + \boldsymbol{t}_k)||^2 , \qquad (3)$$

where k and l are the indices of overlapping scan pairs. Minimization of (3) solves the SLAM problem and uses linearization and least squares and proceeds by solving a system of linear equations. The implementation can be found in *3DTK – The 3D Toolkit* (Andreas Nüchter et al., 2011).

Calibration Cameras and 3D Laser Scanners. Each sensor perceives the world in its own local coordinate system. To join the perceived information we need the specific parameters of these coordinate systems. For combining the 3D point information with the data acquired by the thermal and DSLR cameras calibration between the sensors is necessary, i.e., the relative poses between the sensors have to be known. Since the cameras are mounted on top of the scanner the relation remains the same. To achieve the full horizontal field of view the scanner head rotates around the vertical scanner axis when acquiring the data. We take advantage of this feature when acquiring image data as the cameras are rotated with the scanner head. We acquire 10 images with each camera during one scanning process to cover the full 360°.

After acquiring the 3D data it has to be merged with the color information. This processing consists of four steps:

Intrinsics of thermal and optical cameras. Each camera has unique parameters, namely distortion coefficients and intrinsic parameters, that define how a point in world coordinates is projected onto the image plane.

To determine the parameters of optical cameras chessboard patterns are commonly used because the corners are reliably detectable in the images (Zhang, 1999). A number of images showing a chessboard pattern with known number and size of squares are recorded. In each image the internal corners of the pattern are detected and the known distance between those in world coordinates allows to formulate a non-linear least squares problem to solve for the calibration parameters.

For low resolution thermal cameras a chessboard pattern is more error-prone even after heating it with an infrared lamp. Instead a pattern with clearly defined heat sources such as small lightbulbs is used as it shows up nicely in thermal images thus enabling one to perform intrinsic calibration in the same way as for optical cameras. To detect the light bulbs in the thermal

Fig. 4. Left: Irma3D in Bremen downtown. Right: 3D model with mapped color coded temperature information.

image a thresholding procedure is applied to create a binary image showing regions of high temperature. A further thresholding step discards effectively all regions that are too big or too small. If the remaining number of regions is equal to the number of lightbulbs in the pattern the regions are sorted according to the pattern.

Extrinsic calibration – cameras and laser scanner After calculating the internal camera parameters we need to align the camera images with the scanner coordinate system, i.e., extrinsic calibration. The 3 rotation and 3 translation parameters, known as the extrinsic camera parameters, define the geometric relation between cameras and laser scanner. Once all the points are in the camera coordinate system the projection to the image is defined up to a factor.

Suppose there are n images of the calibration pattern and m planar points on the pattern considering the distortions as independent and identically distributed noise then the maximum likelihood estimate of the transformation between the scanner and camera coordinate system is obtained by minimizing a non-linear equation system (Bradski and Kaehler, 2008). This approach assumes a number of points identifiable in both the laser scan and the image. We attach the calibration pattern onto a board. For the optical camera this is a printed chessboard pattern and for the thermal camera light bulbs arranged in a regular grid pattern. The position of the points of these patterns are known. A brief evaluation of the precision of the calibration process is given in (Borrmann et al., 2012).

3D to 2D projection and color mapping During the data acquisition phase laser scans and images are acquired simultaneously. After determining the relations between scanner and cameras in the calibration step this relation is used directly to color the point cloud according to the images.

Projection/occlusion/resolution errors Due to the different fields of view the sensors see different parts of the world. An area that is visible for one sensor might be occluded for the other sensor. When mapping the color information to the point cloud this causes wrong correspondences and therefore faulty colored points. This impact is increased by the low resolution of the thermal camera. With only 120 by 160 pixels per image each pixel corresponds to many 3D points seen by the laser scanner leading to errors at jump edges. Consequently small calibration inaccuracies have a large impact on the results. To solve this problem we take advantage of the fact that if a point belongs to an object there will be more points on that object. We take all points that are projected onto one pixel and its neighboring pixels. The points are clustered depending on their distance to the scanner. A heuristic based on distance to the 3D scanner and size of the cluster determines effectively which points are considered and enhanced with color information. This removes also some correct color information but the improvement prevails.

The complete environment model can be inspected in the viewer from 3DTK enhanced with either reflectance values, thermal data or color from photos. Switching between the different views enables the user to detect sources of wasted energy and to locate them clearly in the more realistic optical view. Object recognition algorithms are applicable to identify heat sources in the optical data. Future work will concentrate on this aspect.

3.1 Thermal 3D Mapping

Thermal imaging is state of the art in recording energy related issues. However the acquired images tell the user precise temperatures without the dimensions of the heat or air leak. Reliable solutions to 3D reconstruction based on images have not been presented, yet. The robot Irma3D enables us to gage the environmental structure in 3D and thermal information simultaneously. Precise thermal 3D models will enable architects and construction engineers to inspect the model, run simulations of heat and air flow and use the gained information to modify existing buildings to reach the estimated energy savings. Fig. 4 shows an experiment in Bremen downtown. The robot acquired a 3D model of the city center, which was enhanced by thermal information. An animated flight through the acquired 3D point cloud is available under the following link: `http://www.youtube.com/watch?v=TPoCebERysc`

Fig. 5. Left: Irma3D in Ostia Antica. Right: 3D model.

3.2 3D Mapping of Archaeological Sites

The built system enables to work without markers or targets and enables surveyors to save more than 75% of the time spent in the field. This makes the system an ideal solution to map archaeological sites as it reduces the impact to these sites. The robot Irma3D was employed in Ostia Antica, the location of the harbor city of ancient Rome, which is now a large archaeological site close to the modern Ostia, a suburb of Rome. The resulting 3D model can be inspected afterwards and it enables researchers to draw conclusions, in this case about the usage of the garden houses. A video of the robot and the 3D model is given under the following link: `http://www.youtube.com/watch?v=sf-gq5xlaIc`

3.3 3D Mapping of Museums

To attract visitors museums want to promote their exhibitions in a realistic way. A 3D color model created with Irma3D can be visualized on a computer screen and presents a good overview of an exhibition (see Fig.). This was demonstrated at the interactive science exhibition in the Universum Bremen. The goal of the experiment was to create a complete digital 3D model of the special exhibition "Your life in numbers" that presented facts, sculptures and interactive stations demonstrating the statistics of human life. This experiments was a first test for solving the art gallery problem in 3D. In the art gallery problem Irma3D has to calculate the optimal next best scanning position to fully capture the environment. As many exhibits are hanging from the ceiling full 3D information is necessary. A video demonstrating the experiment is available from: `http://youtu.be/p4I-aYEvrTo`.

4. CONCLUSION

The paper has presented a reliable robot for remote inspection tasks. It automates terrestrial laser scanning and the work of a surveyor. The resulting high-precise 3D point cloud is enhanced by thermal or color information. In future work, we concentrate on autonomous exploration strategies.

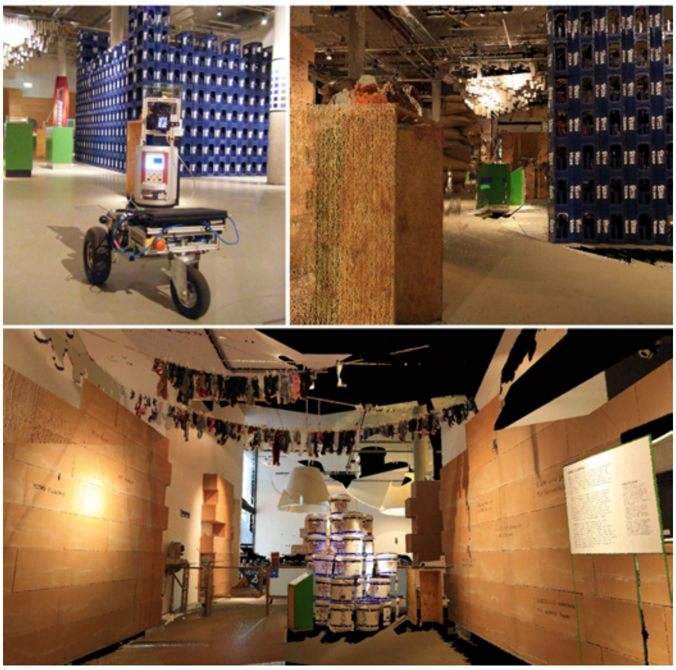

Fig. 6. 3D model from the Universum Science Museum in Bremen. Upper Left: Irma3D collecting the data.

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