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**ORIGINAL ARTICLE**

# Virtobot – a multi-functional robotic system for 3D surface scanning and automatic post mortem biopsy

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## Abstract

**Background** The Virtopsy project, a multi-disciplinary project that involves forensic science, diagnostic imaging, computer science, automation technology, telematics and biomechanics, aims to develop new techniques to improve the outcome of forensic investigations. This paper presents a new approach in the field of minimally invasive virtual autopsy for a versatile robotic system that is able to perform three-dimensional (3D) surface scans as well as post mortem image-guided soft tissue biopsies.

**Methods** The system consists of an industrial six-axis robot with additional extensions (i.e. a linear axis to increase working space, a tool-changing system and a dedicated safety system), a multi-slice CT scanner with equipment for angiography, a digital photogrammetry and 3D optical surface-scanning system, a 3D tracking system, and a biopsy end effector for automatic needle placement. A wax phantom was developed for biopsy accuracy tests.

**Results** Surface scanning times were significantly reduced (scanning times cut in half, calibration three times faster). The biopsy module worked with an accuracy of 3.2 mm.

**Discussion** Using the Virtobot, the surface-scanning procedure could be standardized and accelerated. The biopsy module is accurate enough for use in biopsies in a forensic setting.

**Conclusion** The Virtobot can be utilized for several independent tasks in the field of forensic medicine, and is sufficiently versatile to be adapted to different tasks in the future. Copyright © 2009 John Wiley & Sons, Ltd.

**Keywords** virtopsy; robotics; biopsy; surface scanning; photogrammetry; post mortem; autopsy

## Introduction

Virtual autopsy, or Virtopsy® (1), originated with the goal of implementing radiological diagnostic imaging techniques [computed tomography (CT)/magnetic resonance imaging (MRI)] (2), three-dimensional (3D) photogrammetry and surface scanning, post mortem and minimally invasive biopsy for the benefit of forensic science. In 2000, it was presented as a systematic approach to complement or substitute for standard forensic procedures (3). The aim of the Virtopsy project is to establish an observer-independent, objective and reproducible forensic assessment method with digitally storable results. The use of medical imaging techniques to support autopsy procedures has become more and more accepted in the forensic community. By fusing different diagnostic modalities, it is possible to depict a variety of injuries in a non-invasive manner without opening the body, thus avoiding destruction of potential evidence. Photogrammetry and surface scanning provide highly detailed and fully textured surface data, which can be matched to potential murder weapons or damage-inflicting materials. Investigations at a cellular level can be performed with histology. Body fluids such as blood or cerebrospinal fluid (CSF) can be used for toxicological analysis. However, these techniques require uncontaminated samples of body fluids and tissue samples, which cannot be delivered reliably by standard autopsy methods. Image-guided biopsy is therefore part of the Virtopsy project.

In order to perform a broad range of repetitive tasks with both high speed and accuracy in the field of forensic medicine, a multi-functional robotic system named the Virtopsy Robot, or Virtobot, was developed. Because of their high accuracy, robots have been used to enhance the outcome of a range of medical interventions (4). In combination with CT, they allow for precise needle placement for brachytherapy or biopsy (5,6). Coupled with a surface scanner, robots can help to fully automate the task of generating highly detailed surface models (7). However, building a robot that is able to perform different tasks is a challenging endeavour, due to sometimes contradicting constraints, such as the requirement for different distances from the end-effector to the body, different workloads and differing accuracy requirements. Nevertheless, two particular key tasks of the Virtobot discussed in this paper show significant progress at this stage of development: automatic surface scanning and minimally invasive biopsy.

Morphological assessment is a common step in the autopsy process. Digital photogrammetry and optical surface scanning provide the means to collect 3D digital data on external morphologies. Since the resolution of CT- and MRI-based surface models is limited by the slice thickness and contains no colour information, optical surface scanning and photogrammetry are of great value. These can be fused with CT and MRI data to yield a complete and fully textured 3D model of a human body. Based on 3D data models of the internal and external body and digitized presumed injury-inflicting instruments, real data-based reconstructions of traffic accidents and homicides are possible (8–11). Positioning the scanner manually is time consuming and requires two operators with considerable experience. A robot is beneficial for this task, since it allows scanning of predefined positions that have been shown to yield optimal surface scans.

Harvesting tissue samples is a necessary procedure for forensic investigations at the cellular level and is often critical to the outcome. Small lesions may be difficult to detect and incorrect sampling may lead to erroneous results. Image guided (CT-fluoroscope) (12) and navigated biopsy (13) provide the means to accurately localize small lesions, avoiding contamination or incorrect sampling, but these technologies may pose a significant radiation exposure risk to the examiner, who must be trained and skilled in order to achieve reasonable accuracy. Using robotic assistance for this task eliminates examiner exposure while ensuring accurate localization of the biopsy.

This paper introduces our approach to the design of a multi-purpose robotic system that integrates CT, surface-scanning, photogrammetry, biopsy and angiography technologies to address different challenges in forensic medicine.

# Materials and Methods

## The Virtopsy system

The Virtopsy system at the Institute of Forensic Medicine in Bern, Switzerland, consists of the following main components: a multi-slice CT (MSCT) scanner (Somatom Emotion 6, Siemens, Germany), a modified heart–lung machine for postmortem angiography (HL20, Maquet, Germany) (14), a high-resolution optical digitizing system (TRITOP/ATOS, GOM mbH, Germany), a high-precision optical tracking system (Optotrak, NDI, Canada) and the Virtobot sub-system, which includes a robotic manipulator that can be equipped with different end-effectors.

## The Virtobot sub-system

The Virtobot sub-system was developed by PROFACTOR GmbH (Steyr-Gleink, Austria). Its main motion components include a six-axis robotic arm (Stäubli TX90L Robotic Arm, Stäubli AG, Switzerland) and a 4 m long ceiling-mounted linear axis (Figure 1). The six-degrees of freedom arm has a maximum load capacity of 15 kg, a reach of 1.2 m and a positioning repeatability of ±0.035 mm, according to ISO 9283. This particular manipulator was selected for its high protection class, slim housing and payload : workspace ratio. The working volume of the robot (manipulator + linear axis) was designed to accommodate access to the entire subject, provide a safe space for tool changing and provide a parking position that ensures enough free space around the subject for CT scanning and examiner access (Figure 2). Currently, two interchangeable end-effector modules can be attached to the robotic arm to perform body surface scanning and needle-placing tasks.

## 3D surface scanning and photogrammetry

Precise 3D surface models are generated with an end-effector module that incorporates the GOM TRITOP/ATOS III system (GOM, Braunschweig, Germany).

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**Figure 1. Virtobot set-up with CT scanner, Virtobot with mounted surface scanner and Optotrak tracking system in the background**

**Figure 2. Tool stand with Virtobot in parking position. Left to right: needle holder, surface scanner and biopsy module. Bottom right: needle placement sequence with (a) needle retracted and (b) needle extended**

The TRITOP component of this system is based on multi-image photogrammetry (15,16). Digital photos are taken with a Nikon D2X digital camera (Nikon Corp., Japan) and submitted wirelessly to the TRITOP system. Coded reference targets and scale bars are applied to the body, and their position is automatically calculated during photogrammetry. These data are then used to automatically fuse the surface scans performed with the ATOS component. The images taken are also utilized to texture the surface models.

The ATOS optical surface-scanning system is based on the principle of triangulation. The sensor head consists of a projection unit in the middle and two CCD cameras mounted beside the projector. Fringe patterns are projected onto the surface of the measuring object and observed by the cameras. The data are transferred to the computer and the software calculates up to 4 million 3D surface points per single measurement within seconds. The optimal scanning distance of the surface scanner is 61–103 cm.

## Robot-assisted biopsy

The biopsy module used in this system was developed to accurately place introducer needles to biopsy regions identified by our custom planning and navigation software. The robotic biopsy end-effector (PROFACTOR GmbH, Austria) consists of a linear pneumatic actuator that can apply 70 N (max) of force over 100 mm of travel, a pneumatic gripper for holding and releasing biopsy needles, an array of optoelectronic markers that can be tracked by the navigation system to confirm positioning, and a targeting laser that identifies the skin piercing point for manual incisions to aid needle introduction and minimize needle bending.

The automatic biopsy cycle begins with the robot moving to the needle magazine (Figure 3) to grasp a needle. Once a needle has been acquired, the robot moves to the planned position in two stages: a fast motion to a nearby point, followed by a slower, more accurate and safer motion to the final destination. The tool position is confirmed by the navigation system and corrected automatically if necessary. If incisions are required due to inadequate skin properties, they are performed at this point with the aid of the targeting laser. Finally, the pneumatic actuator, which is the retracted position prior to this point, is fully extended to reach the target point (Figure 2, bottom right). Once the target point is reached, the needle is released by the gripper and the robot returns to the start position of the cycle.

To minimize needle bending during insertion (17), stiffer coaxial introducer needles (13 gauge × 10.3 cm) with symmetrical tips are used in place of standard biopsy needles. This facilitates either manual tissue biopsy using the introducer needles to guide standard biopsy needles, or liquid sampling from the heart or bladder, which is not possible with conventional biopsy needles. Correct localization relative to the plan can be further confirmed following an additional CT scan.

## Semi-automatic tool changing

Differing cable and plug configuration requirements for the two robot end-effectors eliminated the possibility for a fully automated tool-changing mechanism. Therefore, a manual system Schunk HWS 50 (Schunk GmbH & Co. KG, Germany) was selected. During a tool change, the robot moves to the corresponding tool station and stops at a specified distance above the module (Figure 4). The operator then completes the mechanical coupling and cable connections between the module and robot manually. A set of dedicated sensors checks for correct tool changing before allowing further processing steps.

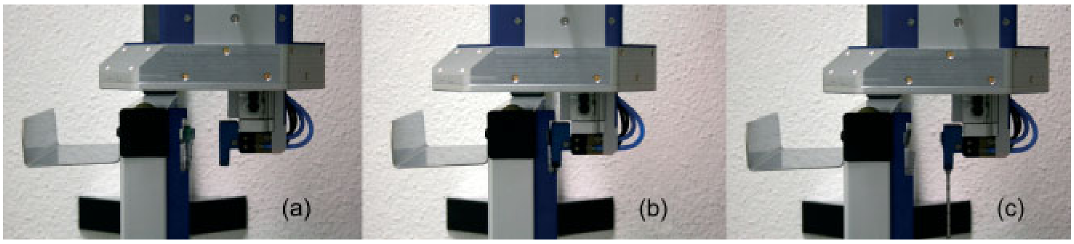

**Figure 3.** Needle grasp sequence: (a) approach the defined needle; (b) grasp the needle; (c) take the needle out of the safety zone to a standby position

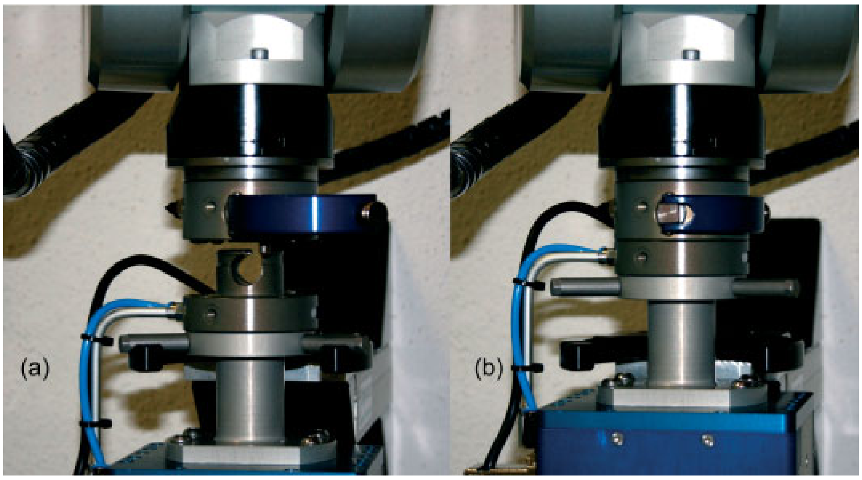

**Figure 4.** Tool-locking mechanism: (a) unlocked and (b) locked

## Safety issues

Due to the complex equipment and process requirements of the Virtopsy system, several standard and custom safety protocols have been devised and implemented. For example, a light curtain (Safety Class 4) installed at the entrance to the robotic cell complements the standard button-operated emergency stops and suspends robot movement immediately. A key-operated bypass of the light gate is also available, which completely restricts robot motion to allow safe access to the robotic cell in order to perform manual operations (e.g. changing tools, performing skin incisions). The system state is indicated visually by a signal lamp. A second light curtain, installed along the housing of the CT-scanner, protects against collisions between the robotic arm and the CT scanner (safety class 2) and is also wired into the emergency stop circuit of the robot.

In general, the maximum speeds of moving elements have been reduced to an appropriate value for each application. Movements considered to be safe are performed at higher speeds than movements for more critical processes or in more critical areas. For example, the area close to CT as well as the area around the tool stand is critical, due to the potential for hardware damage. The Virtopsy robot controller (VRC) allows only predefined motion of the robot in these areas and has specific protocols for emergency stops (Figure 5).

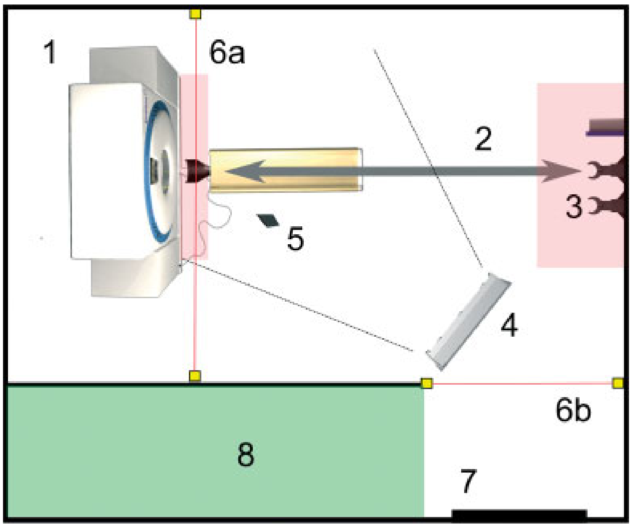

**Figure 5.** Plan view of the Virtopsy examination room: 1, CT scanner and safety area; 2, motion range of the Virtobot on its linear axis; 3, tool stand with low-speed safety area; 4, ceiling-mounted Optotrak tracking system with view volume; 5, world marker shield mounted to the floor; 6, light barriers; 7, entrance; 8, X-ray shielded workstation area

All robot cabling up to the end-effector remains connected to a switch box on the distal arm of the robot at all times, eliminating the potential hazard of disconnected cables. Each end-effector tool has a unique identification number that is checked at every tool change.

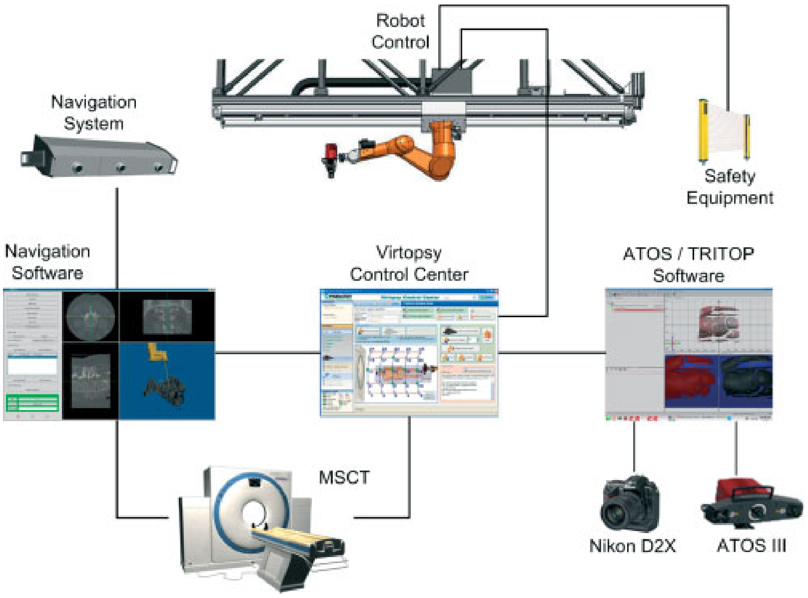

**Figure 6.** Structure of the Virtobot system. The Virtopsy control centre synchronizes different hardware and software packages to gather complex multi-modal information

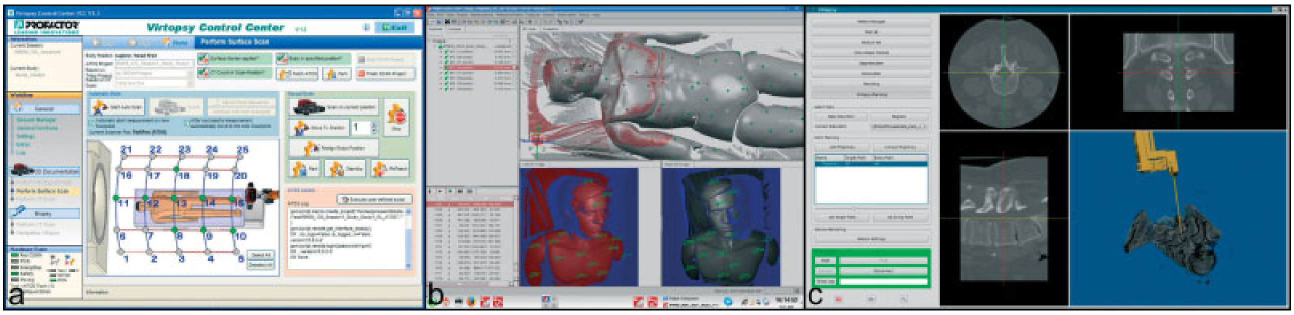

**Figure 7.** Screenshots of software packages in use. (a) Virtopsy control centre (VCC): selection of scanning positions for surface scan. (b) Screenshot ATOS: surface model composed several single surface scans. (c) Screenshot planning and navigation station: trajectory-planning module with multi-planar reconstruction and volume representation of a CT dataset. Final position of the robot is superimposed

This identification ensures that the robotic system is aware of the tool it is carrying, and therefore of its geometric extent, so as to avoid collisions.

## Software

Several software packages are used to control and monitor the functions of the Virtopsy system. These packages are distributed on different computers with different operating systems (Figure 6), but are all controlled and managed remotely by a single software package, the Virtopsy control centre (VCC), via standard TCP/IP communication protocols.

## Virtopsy control centre (VCC)

The VCC (PROFACTOR GbmH, Austria) is a custom software package that coordinates all the other software packages of the system (navigation and planning software, photogrammetry and surface-scanning software and robot control) while providing basic functionality of its own, such as process parameter control, a patient database, basic failsafe mechanisms for the robot and debugging (Figure 7). Once a 3D surface-scan project is started, several predefined robot positions for scanning can be selected. The scanning process for all selected positions and involving all necessary applications is done automatically by the VCC. This system prevents the robot from running into singularities and is sufficient for standard scans. If necessary, special regions of the body can be scanned more accurately by manually adjusting the robot position via the VCC. Guided by the VCC, the operator can initiate and manage CT scans of the body. The VCC links diagnostic information, processes data from photogrammetry and surface scanning and stores the data appropriately for the specific patient. The session manager collects all data produced and documents the whole process of the Virtopsy procedure. The VCC guides the user through the entire Virtopsy workflow and reminds the user to perform necessary steps by means of checkboxes. Until checked, functions that require user action are blocked. Examples for such checkboxes include placing the floor marker shield for biopsy and positioning the CT table at a predefined height for surface scanning. This way, the user follows a predefined, standardized protocol, even with little training.

## Virtopsy robot control (VRC)

The VRC application (PROFACTOR GmbH, Austria) is responsible for coordinating the motion elements of the Virtobot (robot and external axis). It interprets and executes the high-level robot commands from the VCC. To ensure collision avoidance, every motion is precalculated in the VRC, using volume obstacle avoidance algorithms, before any motion actually takes place. Additionally, dangerous areas (such as the CT scanner) are protected by safety equipment hardware.

## Photogrammetry and 3D surface-scanning software for documentation of external findings

Photogrammetry and 3D surface scans are driven by the applications GOM TRITOP (version 6.1.4) and GOM ATOS (version 6.1.4), which run under Linux. A series of macros that can be executed remotely by the VCC have been implemented for the creation and storage of relevant data (Figure 7). The ATOS software can also be used to calibrate the surface scanner if the lenses have been changed or the accuracy of the system is decreasing. For this, a special calibration phantom is scanned from different positions and angles.

## Planning and navigation application

Trajectories for the biopsy procedure are defined in the planning and navigation software (Artorg Research Centre and Institute of Forensic Medicine, University of Bern, Switzerland), which is based on the Co-Me medical application framework Marvin (18), developed at the Artorg Research Centre (Bern, Switzerland). Its functionality includes a patient database, DICOM support, modules for registration and trajectory planning and a TCP/IP interface to the VCC. Trajectory data include the target point, the entry point of the needle and the orientation of the robot. The orientation is necessary to plan a collision-free needle release motion as well as to position optimally the marker shield relative to the tracking system. In combination with the known penetration depth of the linear pneumatic actuator, the final position of the robot can be calculated. After a reachability check with the VCC, the trajectory data is submitted and the needle placed by the robot accordingly (Figure 7).

## Transformations

There are a number of coordinate systems used to define the spatial position of objects and data in the Virtopsy system (Figure 8): a camera coordinate system (CCS), a robot coordinate system (RCS) and an image coordinate system. Optical tracking is performed in the CCS, where the relative position of the image data, body and robot can be determined. The image is registered to the optoelectronic marker shield attached to the body by using paired point matching (19) and the restricted surface-matching algorithm (20). Positions of the robotic end-effectors are defined in the RCS, which has its origin

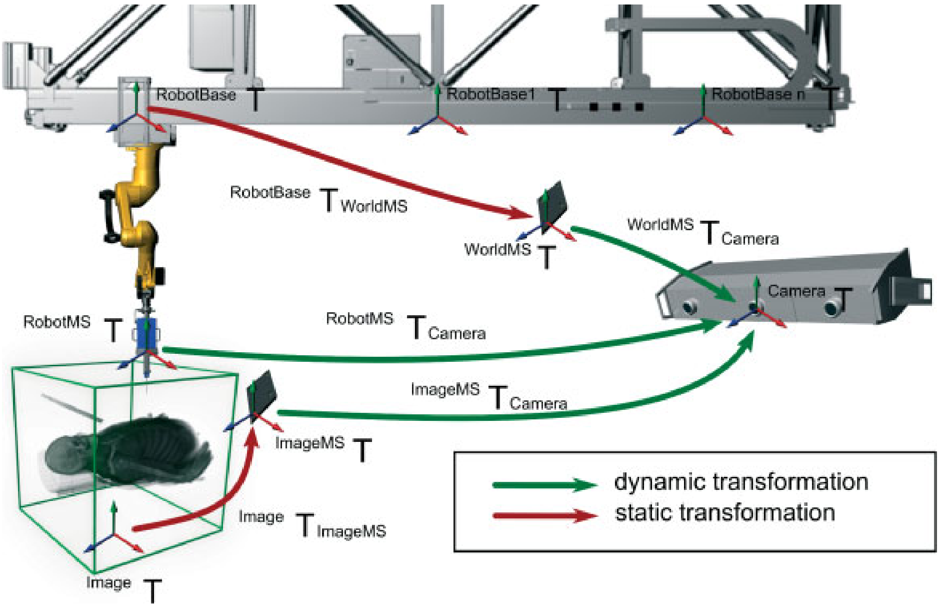

**Figure 8. Transformations used for biopsy. Green transformations are generated by optical tracking of optoelectronic marker shields; red transformations are rigid and registered once**

at the robot's base and therefore moves along with the external axis carriage. Trajectories are planned in the local image coordinate system of the CT, and must be converted to the RCS to correctly drive the robot. The transformation between these coordinate systems therefore must be known. This transformation is determined by introducing an optoelectronic marker shield that is rigidly attached to the floor and serves as an anchor between RCS and CCS. The robot is pivoted around a series of points in space while optically tracking the marker shield. The pivoting centre is calculated and paired point matching is then applied to both point sets, as shown in Figure 9. This calibration is repeated for predefined positions of the external axis.

The transformation from the image coordinate system to the RCS is then calculated by:

$$^{Image}T_{RobotBase} = \left(^{RobotBase}T_{WorldMS}\right)^{-1} \cdot \left(^{WorldMS}T_{Camera}\right)^{-1} \cdot {}^{ImageMS}T_{Camera} \cdot {}^{Image}T_{ImageMS}$$

After positioning the robot at a planned location, a correction vector can be determined by transforming the tracked position of the robot to the image coordinate system and comparing it to the planned trajectory:

$$^{RobotMS}T_{Image} = \left(^{Image}T_{ImageMS}\right)^{-1} \cdot \left(^{ImageMS}T_{Camera}\right)^{-1} \cdot {}^{RobotMS}T_{Camera}$$

The calculated correction vector is then shifted back to the RCS by applying $^{Image}T_{RobotBase}$. The correction function can be used, to correct for accidental body motion after registration.

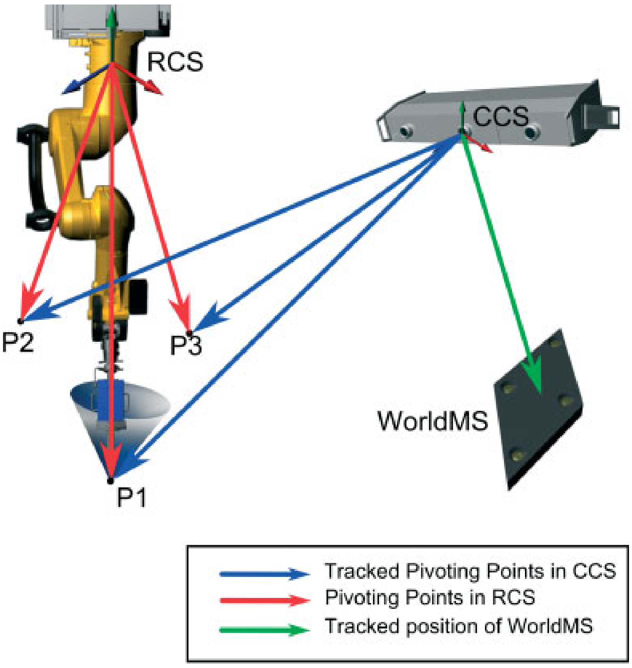

**Figure 9. Calculating $^{RobotBase}T_{WorldMS}$ by pivoting the Virtobot while tracking**

## Biopsy phantom and accuracy measurement

To measure the accuracy of the biopsy module, a phantom was developed based on the one designed for our manual biopsy accuracy study (13). Unlike the original phantom, the new phantom is composed of a combination of wax and oil instead of gelatin. In this way, increased stability of the introducer needle and better CT contrast can be obtained. After removing the needle, its path can be clearly displayed on a CT volume dataset (Figure 10). For registration, six radio-opaque markers were attached to the phantom. Peas were embedded within the wax to act as biopsy targets. For every needle placement, the whole workflow including calibration and registration was repeated, not including the correction function. The accuracy after needle placement was determined by performing a second CT scan, prolonging the needle trajectory and measuring its distance from the centre of the pea. Registration and calibration accuracy was determined by calculating the RMS.

# Results

## Virtopsy workflow

The workflow of a Virtopsy examination is implemented and supervised by the VCC. This workflow requires the initial placement of coded markers and scale bars for photogrammetry and uncoded markers for the automatic fusion of the single surface scans, as well as radio-opaque markers to provide information for the fusion of the CT and surface data (Figure 11).

A Virtopsy procedure can include the following steps, depending on the desired output:

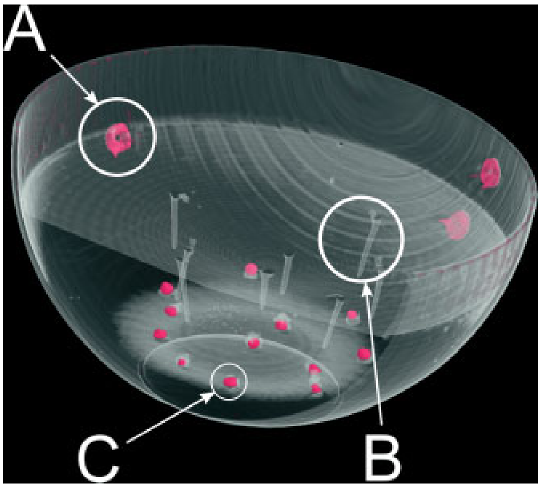

**Figure 10. Volume rendering of the biopsy phantom showing radio-opaque markers (a) needle trajectories (b) and targets (c)**


[redacted]

**Figure 11. 3D dataset of a suicide headshot, composed of CT, MRI and surface-scanning data. (Top left) Coloured 3D surface model of the muzzle imprint. The entrance wound is surrounded by non-coded reference targets and multi-modality radiographic markers**

- Photogrammetry.
- Surface scanning.
- CT/angiography.
- Biopsy.

For photogrammetry, the body is placed in a supine position on a vacuum mattress that keeps it stable for moving or turning. The photogrammetric images are taken free-hand from different viewing angles and automatically transferred to the TRITOP software via wireless LAN and processed.

After calculating the photogrammetric images, the coded reference targets are removed and the surface scanner is mounted to the robot. The scanning positions are selected in the VCC and a whole-body scan is then performed automatically. Following surface digitization, a CT scan is performed. Angiography may also be performed at this time if required.

To perform a robotic biopsy, radio-opaque markers are attached to the body and used for image registration and fusion of the different modalities used. Planned needle insertion trajectories are sent to the control station and, after a validity check, introducer needles are automatically placed by the robot. A second CT may be performed at this time to confirm placement and then the actual biopsies are performed manually, using the introducer needles as guides.

## Virtobot surface scanning

Since its installation in 2008, the Virtobot has provided robotic assistance for automated surface scanning in 52 cases: 26 victims of traffic accidents, 10 cases of blunt trauma, six knife wounds, five gunshot wounds, three scans of bite marks and two cases of strangulation. Of those 52 cases, 19 scans were included in court forensic reports, all of them showing damage-inflicting structures in relation to wound topology. Three cases were published in scientific journals. With a tripod, a manual surface scan of one side of a victim takes approximately 30 min. By using the Virtobot, this time was decreased to approximately 15 min. Calibration time of the scanner was reduced from 12 to 4 min using the robotic system.

## Virtobot biopsy: preliminary accuracy study

In order to determine the accuracy of needle placement, a preliminary accuracy study was performed based on the wax biopsy phantom. Calibration of the robot to the world marker shield was performed with six pivot points and a mean RMS of 2.3 mm ($\pm 0.04$ mm, $n = 13$). The cone centre for every pivot point was determined with an accuracy of 0.5 mm (0.06 mm, $n = 78$). Two phantoms were prepared and a total of 13 needles were set. The mean accuracy was 3.2 mm ($\pm 1.9$ mm, $n = 13$).

# Discussion

## Summary and next steps

The Virtobot is the robotic component of the Virtopsy platform, which was integrated into the system in early 2008 and extended with the biopsy module beginning of

2009. This tool was designed to automate some of the more complex or laborious manual operations performed during a forensic exam, while improving accuracy, increasing speed and reducing operator exposure to radiation or infectious body fluids. Currently, the Virtobot comprises a robotic manipulator, external linear motion axis, two different end-effectors and dedicated control hardware and software. The two end-effector modules include one that facilitates automatic surface scanning of a body and another that facilitates robot-assisted biopsies.

Several challenges arose during the integration of the Virtobot into the Virtopsy system, including: selection of components for operational flexibility, carriage loading, data collection and operator and equipment safety; integration of the robotic motion control with the planning and navigation, surface-scanning and photogrammetry software applications; design of end-effectors to perform surface scanning and biopsy functions; and calibration and verification of the various devices used to ensure accurate operation.

The design of the Virtobot's motion components is sufficiently flexible to provide positioning and articulation that accommodates both surface-scanning and biopsy modules, despite their substantially different requirements. Surface scanning is performed in an envelope around the body at an optimal distance from its surface, while biopsies require the robot to work within the body volume and in close proximity to the body and CT table.

Different independent software packages, such as CT software, Syngo MMWP (VE23A, Siemens AG, Germany), TRITOP, ATOS and Marvin, are integrated by the VCC to fit the needs of forensic medicine. The VCC application guides the user through the standardized process of a Virtopsy and synchronizes the different software packages in use. This helps to minimize errors and leads to better, more reproducible results.

## Surface scanning

The set-up described above was installed at the Institute of Forensic Medicine Bern in Spring 2008, and has been used in daily routine since then. The surface-scanning procedure, which has been used manually and has proved to be a valuable tool over the last 6 years, could be further optimized by integrating it to the Virtobot system.

A standard manual surface scan requires the operator to move the stand with the mounted scanner to optimal scanning positions. Usually, two persons are required for this procedure – one moving and placing the sensor head, and the other operating the system and supervising the measurements. By using the Virtobot for surface scanning, we now can assure optimal results by placing the scanner within the optimal scanning distance of 61–103 cm for every corpse. Due to the extensive automation, the surface-scanning module can be operated without special training after a quick introduction, and the system can be used by a single operator. The overall scanning and calibration times could be reduced significantly by additionally optimizing the workflow.

## Next stage – CT-guided biopsies

The combination of the Virtobot with a CT scanner and an optical tracking system allows for robotic biopsy based on CT imaging while limiting the examiner's exposure to radiation or potentially infectious body fluids. For standard forensic biopsies, an accuracy of <5 mm is required, which is already accomplished by the system as shown. However, an accuracy of 2 mm or better is expected for scientific purposes. Our preliminary study identifies the registration of the robot to the world coordinate system as the main source of error. Although the pivoting error during calibration is small, the combination of different pivoting points through paired point matching led to a much larger error; however, we believe that a bad calibration of the tracking system or a high absolute positioning error of the robot might lead to this calibration error. Apart from this, the definition of pivot points has a direct influence on the outcome of the registration, and an optimal positioning has yet to be determined. Therefore, further tests of the accuracy of components involved and the definition of better pivot positions are necessary.

Although a radiologist is required to interpret the CT data and identify biopsy targets, trajectory planning and biopsy can be performed with very little training. The planning and navigation software can be decoupled from the rest of the system, which theoretically allows for telebiopsy, in which trajectories could be planned by experts not present in the Virtopsy examination room. Currently, registration of the CT dataset to the marker shield is done manually, which is time consuming and requires a second person. Increasing the accuracy and implementing an automatic registration algorithm are future developments towards optimizing the biopsy procedure. Although the first tests look promising, the results should be confirmed via an extensive accuracy study before starting trials on human cadavers.

## Further possible extensions of the system

Development of the Virtobot is ongoing. Among the various planned optimizations, the next step is the development of a module that is able to perform the photogrammetry procedure in a more automated manner. The current use of flashlights reduces the overall texture quality, due to shadowing. At the moment, additional images are taken with a tripod, using long exposure times, to overcome this problem. Mounting the photographic camera on the robot arm could replace and fully automate this time-consuming procedure. Additionally, this could eliminate the necessity of placing coded and uncoded reference markers, since the exact positions of the robot during imaging and surface scanning are known to the system for further calculations.

# Conclusion

This paper introduces a new concept for a versatile robotic system that is able to perform different independent tasks in the field of minimally invasive virtual autopsy. A surface-scanning module has been developed as along with a module for robotic CT-based biopsy. Other modules, such as for automated photogrammetry, are under currently development or are being evaluated. The system described here allows for constant quality of recorded data and has a short training time. Despite the high initial costs of the complete system, including CT, navigation, surface scanner and robot, the Virtobot system has already proved to be a useful tool in virtual forensic autopsy and has not yet reached its full potential.

## Acknowledgements

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## Disclosure

PROFACTOR GmbH is planning to commercialize the Virtobot and the VCC software after its successful evaluation.

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