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ORIGINAL ARTICLE

Trauma Pod: a semi-automated telerobotic surgical system

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Abstract

Background The Trauma Pod (TP) vision is to develop a rapidly deployable robotic system to perform critical acute stabilization and/or surgical procedures, autonomously or in a teleoperative mode, on wounded soldiers in the battlefield who might otherwise die before treatment in a combat hospital could be provided.

Methods In the first phase of a project pursuing this vision, a robotic TP system was developed and its capability demonstrated by performing selected surgical procedures on a patient phantom.

Results The system demonstrates the feasibility of performing acute stabilization procedures with the patient being the only human in the surgical cell. The teleoperated surgical robot is supported by autonomous robotic arms and subsystems that carry out scrub-nurse and circulating-nurse functions. Tool change and supply delivery are performed automatically and at least as fast as performed manually by nurses. Tracking and counting of the supplies is performed automatically. The TP system also includes a tomographic X-ray facility for patient diagnosis and two-dimensional (2D) fluoroscopic data to support interventions. The vast amount of clinical protocols generated in the TP system are recorded automatically.

Conclusions Automation and teleoperation capabilities form the basis for a more comprehensive acute diagnostic and management platform that will provide life-saving care in environments where surgical personnel are not present. Copyright © 2009 John Wiley & Sons, Ltd.

Keywords medical automation; telesurgery; surgical intervention; teleoperation; trauma stabilization; robotic surgery; operating room automation

Introduction

Medicine in general, and surgery in particular, have experienced a profound change that may augment the physician's ability to perform clinical procedures and deliver healthcare to local and remote sites. For decades, surgery and robotics have progressed separately. In surgery, minimally invasive techniques have revolutionized the way a significant number of surgical interventions are performed. In robotics, teleoperation has been developed by interfacing a human operator and a robotic system through the use of telecommunication, display, speech recognition and generation, and sensors (in particular visual, range, tactile and force sensors). Only in the last decade have surgery and robotics matured to a point that allows a safe merger of the two, thus creating a new kind of operating room (OR) (1–8). Natural disasters and military operation have demonstrated the need for providing for urgent medical care, particularly surgical intervention, on site to individuals with life-threatening injuries in remote locations. Given the nature of these extreme remote environments, providing high quality and specialized medical care in a timely manner for life-threatening injuries, as well as the capability to address complications that are evolved during the evacuation process, requires a substantial logistical operation and specialized human resources on site.

Analysis of the functions accomplished in the OR of today indicates that, in many cases, a surgeon can engage a patient through a surgical robot in a teleoperational mode (9–12). Surgical tool and supply functions (currently handled by a scrub nurse) and OR information (currently managed by a circulating nurse) can be automated.

The ultimate goal of the Trauma Pod (TP) system described in this paper is to produce a rapidly deployable robotic platform, capable of performing critical diagnostics and acute life-saving interventions in the field for an injured person who might otherwise die from loss of airway, haemorrhage or other acute injuries, such as tension pneumothorax. The TP damage-control interventions will be much more invasive and effective than currently available first-aid treatments, and are envisioned only as life-saving measures before the wounded patient reaches a site where conventional medical care is provided. These interventions will involve procedures that preserve life and limb, such as the ability to obtain an airway, insert an intravenous or intra-osseous line, perform haemostasis, manipulate damaged tissues and place monitoring devices. The TP will be used when the timely deployment of proper medical personnel is not possible or too risky and the patient cannot be evacuated quickly enough to an appropriate medical facility.

Materials and Methods

Overview

TP Phase I provides the capability to perform portions of specified surgical procedures via teleoperation by a surgeon. These procedures include placing a shunt in a major abdominal (e.g. iliac) vessel and performing a bowel anastomosis; both procedures entail surgical skills required in a trauma surgery. Eventually, the TP is expected to perform many other procedures entailed in preserving life and limb.

The first objective of Phase I was to demonstrate that these two procedures can be performed by a surgeon teleoperating the surgical robot and supported by automated manipulators performing nursing functions. The second objective was to demonstrate the feasibility of performing full-body CT scans in the field during the operation. All the procedures were demonstrated on phantoms in a controlled environment.

The system was prototyped in a fixed room, using a combination of off-the-shelf and custom systems. The project focused on the process flow and architecture required to accomplish the surgical procedures, rather than on developing hardware for trauma procedures. For example, the surgical robot chosen for Phase I, the da Vinci© robot from Intuitive Surgical (ISI), was not suitable for trauma surgery but was a reasonable surgical robotic platform for demonstrating the flow of tasks during the development of the TP system in Phase I.

The TP system consists of 13 subsystems. The abbreviation and description of each TP subsystem, as well as its developer, are listed in Table 1. The SRS is capable of performing basic surgical functions (e.g. cutting, dissecting, and suturing) through teleoperation. Except for the PRS, the remaining subsystems are capable of autonomously serving the SRS (by changing tools and dispensing supplies, as ordered by the surgeon) and recording every TP activity. Figure 1 shows the physical layout of the main TP components [the SRS, PRS, SNS, SDS (including a Fast Cache) and TRS].

The TP system operates automatically during normal operating conditions and can detect an error, but recovery from an error requires manual intervention by a remote administrator. All subsystems have safe states to which they revert automatically when an error is encountered.

The TP system architecture, shown in Figure 2, is hierarchical. System tasks are initiated by the surgeon and interpreted by the UIS, which issues commands to the SCS, which in turn coordinates all the system tasks. The surgeon has direct control over the SRS through voice commands and a teleoperated joystick interface. The AMS monitors the system status and error conditions, and provides information to a human administrator, who may manually control any subsystem and correct any error.

Table 1. Trauma pod subsystems

	Subsystem	Developer
SRS	Surgical Robot Subsystem	Intuitive Surgical, Inc.
AMS	Administrator and Monitoring Subsystem	SRI International
SNS	Scrub Nurse Subsystem	Oak Ridge National Laboratory
TAS	Tool Autoloader Subsystem	Oak Ridge National Laboratory
SDS	Supply Dispenser Subsystem	General Dynamics Robotics
TRS	Tool Rack Subsystem	University of Washington
SCS	Supervisory Controller Subsystem	University of Texas
PRS	Patient Registration Subsystem	Integrated Medical Systems
PIS	Patient Imaging Subsystem	GE Research
MVS	Machine Vision Subsystem	Robotic Surgical Tech, Inc.
RMS	Resource Monitoring Subsystem	University of Maryland
SIM	Simulator Subsystem	University of Texas
UIS	User Interface Subsystem	SRI International

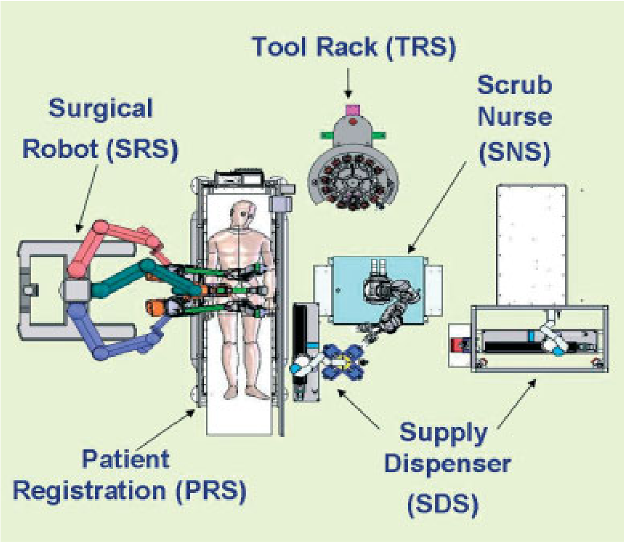

Figure 1. Layout of Trauma Pod main components

The subsystems are loosely coupled, and communicate with each other using XML messages through a gigabit Ethernet network. Each subsystem uses its own operating system with a layer of well-defined interfaces that can accept and send XML messages, using the appropriate format. Subsystem communication includes a command-and-response protocol along with a high-speed exchange of sensory data. Sensory data are shared in an open-loop fashion and are used by the SCS and SNS to generate collision-free SNS trajectories.

Trauma Pod system

The TP system has been integrated, tested and debugged by SRI International. The following capabilities were demonstrated:

- Automatic storing and dispensing of surgical tools by the TRS.
- Automatic storing, de-packaging dispensing and counting of supplies by the SDS.
- Automatic change of surgical tools and delivery and removal of supplies by the SNS.
- Speech-based interface between a teleoperating surgeon and the TP system through the UIS.
- Automatic coordination and interaction between the SRS and the SNS.
- Performing iliac shunt and bowel anastomosis procedures by a teleoperated SRS on a patient phantom.

The TP system, depicted in Figure 3, consists of two major cells: a *control cell*, where the surgery is controlled by the surgeon and monitored by the administrator, and a *surgical cell*, where the surgery is performed by the TP subsystems. In a real application, the two cells will be far

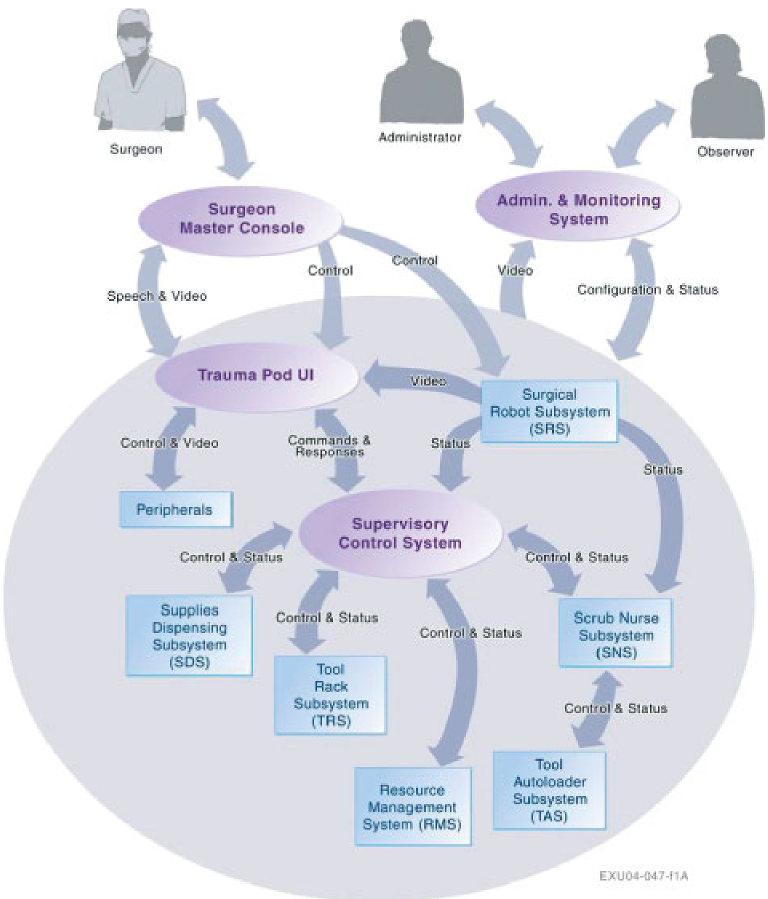

Figure 2. Trauma Pod architecture

(a)

(b)

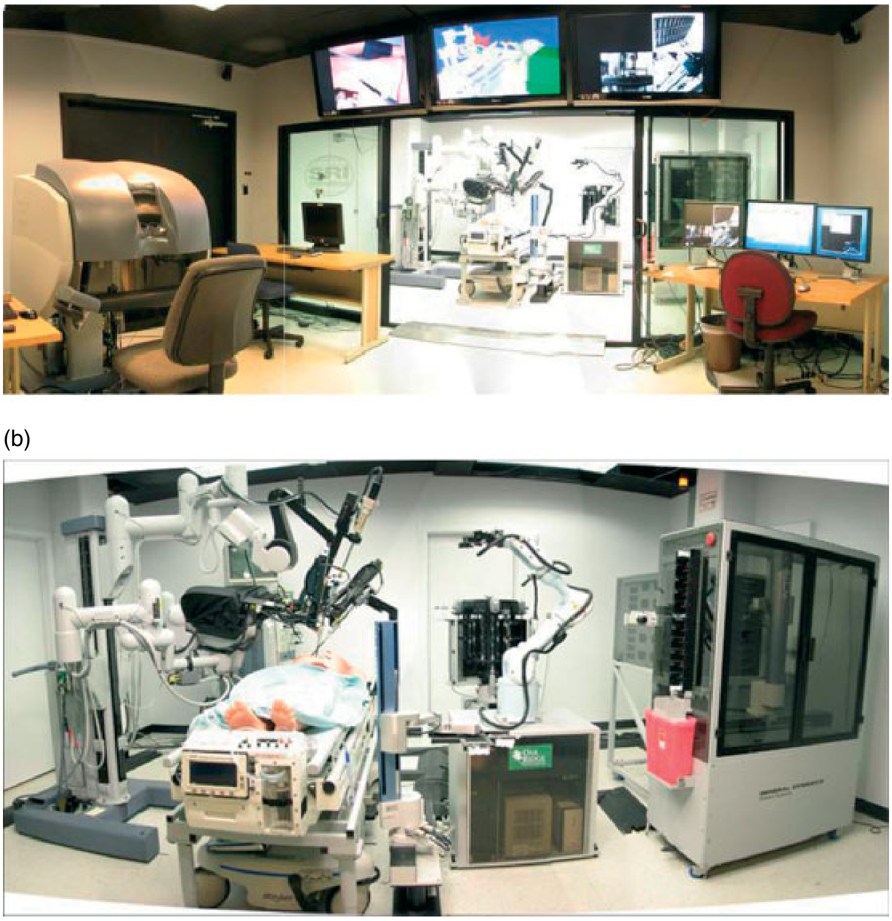

Figure 3. The TP system: (a) control cell; (b) surgical cell

apart: the surgical cell will be deployed in the battlefield or the remote site, while the control cell will be located in a safer place behind; the two cells will telecommunicate via a wideband wireless link. In Phase I of this project, the two cells were located adjacent to each other and separated by a glass wall.

The control cell includes a control station for the surgeon and one for the system administrator. It also contains multiple displays of video and sensory information that assist in controlling and monitoring the surgical cell. The surgical cell contains all the TP subsystems required to perform a surgical procedure. The surgical cell footprint (8×18 ft) can fit within an International Standards Organization (ISO) container for shipment as cargo.

Trauma Pod subsystems

The subsystems that were developed in Phase I of TP are described below.

Surgical robot subsystem (SRS)

The SRS performs surgical procedures on the patient through teleoperation. The SRS consists of two major parts: a surgical master console and a slave surgical robot. The slave robot, a da Vinci surgical system made by Intuitive Surgical Inc., consists of two manipulation arms and an arm accommodating a light source and a stereo endoscopic camera. Video from that camera is sent to the master console view port and, using a pair of haptic (force-sensing) joysticks, the surgeon controls movement of each slave arm over the patient and its surgical manipulation.

Scrub nurse subsystem (SNS)

The function of the SNS, shown in Figure 4a, is to autonomously serve the SRS, following the surgeon's commands. Specifically, the SNS automatically performs three major functions: (a) it delivers supplies from the SDS to the SRS and to the fast cache and it retrieves used and unused supplies; (b) it exchanges tools between the TRS and the SRS, using a dual gripper end-effector (Figure 4b); and (c) it performs geometric calibration and registration of the TP subsystems. Handling of supplies and tools must be done quickly and reliably upon verbal commands from the surgeon. The target goal for each handling task is 10 s or less, which is faster than a typical human performance of each of these tasks.

The SNS control software consists of a Motion Planner (MP), developed by the University of Texas, and a Motion Executor (ME), developed by Oak Ridge National Laboratory (ORNL). The MP generates SNS trajectories, kinematics with redundancy resolution,

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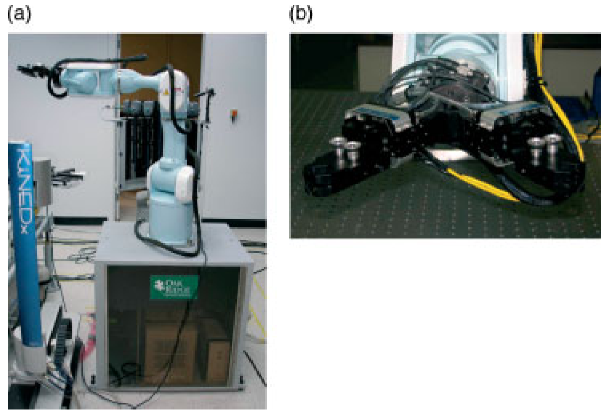

Figure 4. Scrub nurse subsystem (SNS): (a) Mitsubishi PA10 robot on a pedestal base; (b) dual gripper end-effector

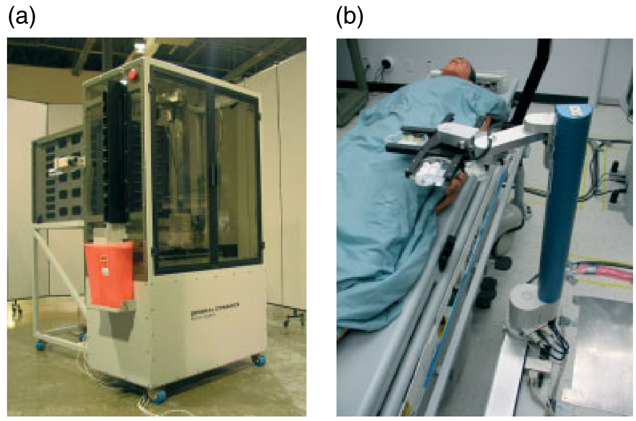

Figure 6. Supply dispensing subsystem (SDS): (a) main unit; (b) fast cache (near patient)

obstacle avoidance, and detection of imminent collisions. A previously developed software framework, Operational Software Components for Advanced Robotics (13–16) (Robotics Research Group) was used in the MP development. The ME is responsible for reaching the SNS joints corresponding to the poses specified by the MP, and for performing low-level force-control operations during contact-based tasks.

In addition, a tool autoloader subsystem (TAS), developed by ORNL, is mounted on either da Vinci arm as an end-effector for capturing and holding a tool (see Figure 5). The TAS is controlled by the SNS controller as part of a coordinated robotic tool-exchange activity.

Supply dispensing subsystem (SDS)

The role of the SDS, developed by General Dynamics Robotic Systems (GDRS), is to store, de-package, dispense and discard used consumable medical supplies. The main unit of the SDS is shown in Figure 6a. The supplies of each type are stored in small trays that are, in turn, stored in a horizontal restocking cartridge.

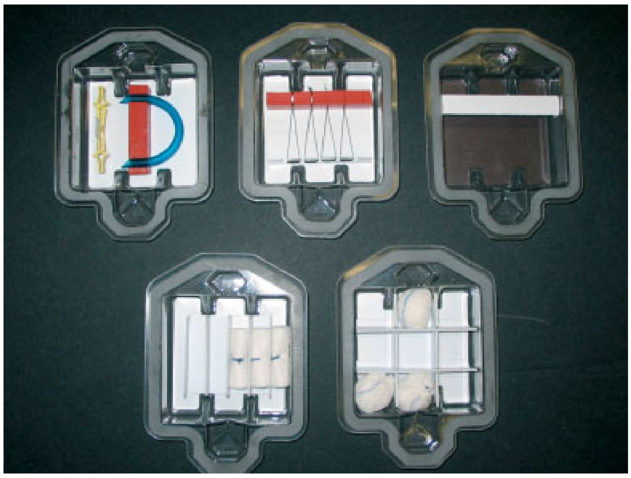

Figure 7. Supply trays. Clockwise from top-left: shunt kit, sutures and ties, waste, spherical sponges and cylindrical sponges

Figure 5. Tool autoloader subsystem (TAS) mounted on a da Vinci arm

Partially used trays are stored in either the fast cache next to the patient bed (Figure 6b) or in a slow cache, which is part of the 10-slot transfer array on the side of the SDS main unit. Waste trays and empty supply trays are identified by machine vision and placed in a medical waste container by the SNS.

The shape and outside dimensions of a tray were the same for all medical supplies. However, different tray inserts were used for each supply type to position supplies in the tray and restrain their motion. Figure 7 shows partially populated supply trays.

Tool rack subsystem (TRS)

The TRS (Figure 8a), developed by the University of Washington, is a fully automated tool changer capable of holding, accepting, and dispensing each of 14 surgical robotic tools (Figure 8b) used by the da Vinci robot and maintaining their sterility (17). The TRS contains a sterilizable round magazine with 15 tool positions.

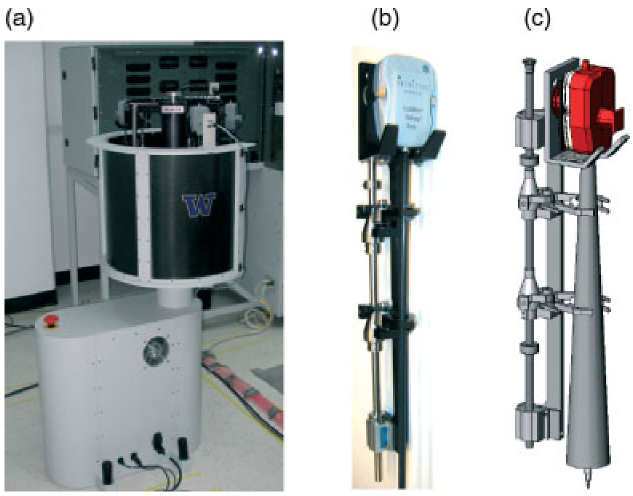

Figure 8. Tool rack subsystem (TRS): (a) overview; (b) surgical tool grasped by tool holder; (c) CAD display of a tool holder grasping a surgical tool under permissible angular misalignment, which is defined by the grey cone along the tool's shaft

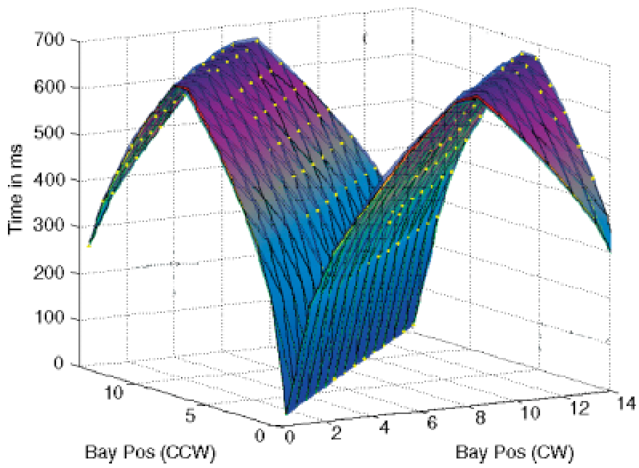

Figure 9. Movement time measured between each possible pair of tool positions during multiple tests ($n = 1350$). Worst case movement time was 648 ± 8 ms

The TRS is able to: (a) dispense and accept a tool that is presented to the TRS within a maximum angular misalignment of 5° (see Figure 8c) by the stiff SNS; and (b) move and present a desired tool to the SNS in a given pose within 700 ms.

The entire tool magazine can be removed from the TRS along with the surgical tools for sterilization in an autoclave. All sensors and actuators are located below the sterile barrier and do not touch the tools.

Radio frequency identification (RFID) tags are located inside of each tool, with a unique 24 bytes identification number. A small form factor video camera mounted on a flexible shaft was pointed at the tool's transfer zone between the TRS and the SNS.

The three most critical performance criteria of the TRS included the ability to: (a) dispense and accept the tools presented to the TRS with a large position and ordination misalignments; (b) absorb the energy introduced by these misalignments, given the significant stiffness of the SNS; and (c) present the tool in a timely manner in a given position and orientation upon request. The results, following an experimental approach, indicated that the misalignment tolerance exceeded by a factor of 2 the worst case misalignment scenario that can be generated by the SNS (Table 2).

The time interval for presenting a tool was in the range 0–648 ± 8 ms (Figure 9) and for releasing the grasping of the tool 98 ± 8 ms.

Table 2. Tolerances of the TRS tool holder

Parameter	Tolerance	Units
Displacement	4	Mm
Orientation	2.8°	(degrees)
Linear stiffness	5.7–7.8	N/mm
Tensional stiffness	0.8	Nm

Supervisory control subsystem (SCS)

The primary function of the SCS, developed by the University of Texas, is to provide high-level control of all the automated subsystems, primarily those performing tool changing and supply dispensing when ordered by the surgeon, and to coordinate these subsystems with the teleoperated SRS. High-level control is achieved by using automated task management and by planning a coordinated execution of tasks to be performed by several subsystems (18,19). Multiple surgeon requests may also be queued by the SCS and executed in sequential order. Secondary responsibilities of the SCS include collision avoidance, subsystem monitoring for inconsistent or unsafe states, and detection of subsystem alarm conditions.

A task may be paused or cancelled by either the surgeon or the system administrator. The SCS can add/remove subsystems to/from a task plan. Task plans can be written and modified independently of changes in the task-management components.

Patient registration subsystem (PRS)

The PRS holds the patient on a platform, scans the patient surface stereoscopically, and creates a three-dimensional (3D) model that allows the TP robots to move safely around the patient. LSTAT, a life-support system made by Integrated Medical Systems Inc., was used as a PRS platform. The LSTAT platform, shown in Figure 10, also provides the means for monitoring vital signs, fluid delivery and a ventilator.

Patient imaging subsystem (PIS)

The PIS, developed by GE Research, includes a tomographic X-ray facility that is compatible with the TP robots and the LSTAT, and capable of generating CT-like datasets for patient diagnosis and 2D fluoroscopic data to support interventions. The PIS consists of an X-ray tube mounted on an overhead rail and capable of moving in a plane above the patient, and a large flat-panel X-ray detector embedded in the LSTAT. This configuration

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Figure 10. LSTAT platform

allows for generation of a sequence of diagnostic 3D images as the detector is moved in a 2D grid-like pattern above the patient for 10–30 s. The sequence of images is then reconstructed, using an algorithm similar to that used in a conventional CAT scan, to generate a 3D image of the patient's interior organs (Figure 11). The PIS may also be operated in an interventional mode, allowing the PIS to support minimally invasive procedures, such as stent or shunt placement.

Machine vision subsystem (MVS)

The MVS, developed by Robotic Surgical Technology, Inc., captures images from cameras positioned around the TP cell and analyses these images in order to track the movement of supplies and tools. The primary function of the MVS was to determine the number of supplies of a given type on each tray moved horizontally by the SNS into and out of the surgical site. The MVS also determines when a supply tray is empty, so that it can be disposed of. The entire supply counting process is currently completed in 0.52 s or less.

Resource monitoring subsystem (RMS)

The RMS, developed by the University of Maryland, automatically records the vast amount of clinical protocols generated in the TP system. The RMS task addresses procedural and nursing documentation.

The RMS monitors and records significant clinical events within the TP, including event times, surgical procedures (e.g. incision, debridement and placement of shunts), medications, fluids and other clinical inputs. In addition, the RMS also monitors supply and instrument usage, and assists in the final counts of items used.

Simulator subsystem (SIM)

The SIM subsystem, developed by the University of Texas, generates a high fidelity 3D display of the TP system and provides real-time animation of the TP subsystems, based on sensory data (Figure 12). The SIM objectives were to provide: (a) means for emulating integrated subsystems in the early stages of the TP development; (b) simulated stereoscopic video feedback to the surgeon in the absence of a phantom patient; (c) assistance in the workspace and layout analysis of the TP. The simulator successfully achieved these objectives by developing a 3D graphical view, based on CAD models of the subsystems, updated at a rate of 30 Hz, with stereoscopic output and multiple camera views. The simulator also included a high-fidelity collision detection and real-time model update based on the manipulator encoders in the system.

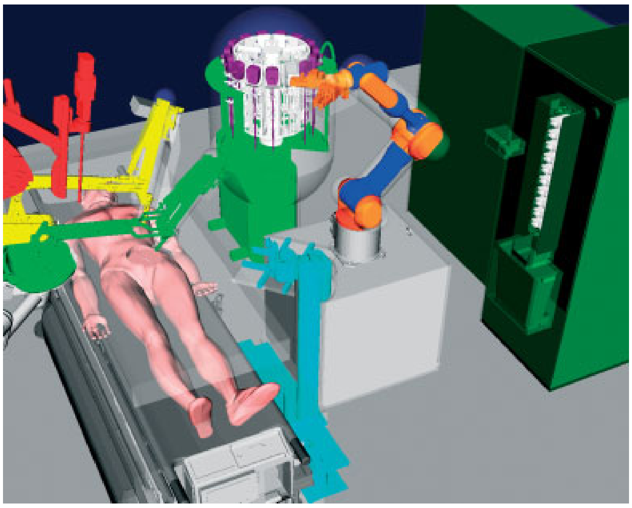

Figure 12. Primitives-based obstacle model

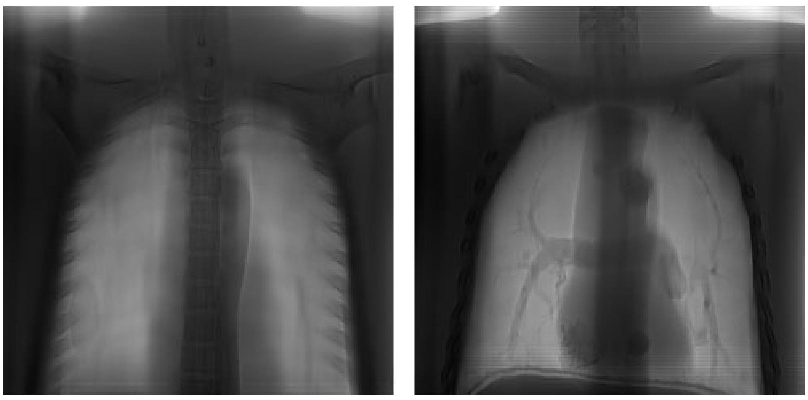

Figure 11. X-Ray tomographic reconstruction of torso phantom, coronal view: (left) slice centred on spine; (right) slice centred on lungs

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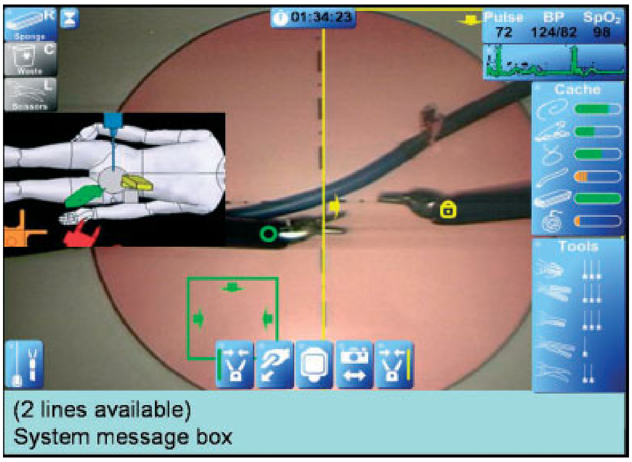


Figure 13. User interface subsystem display (showing all available icons)

User interface subsystem (UIS)

The UIS, developed by SRI International, provides the surgeon with the means and information required to interact with the TP system in a natural and efficient manner. The UIS is specific to a surgeon (a separate subsystem-management interface is provided for a system administrator): it provides visual, verbal, aural and gesture-based interfaces between the surgeon and the TP system, as described below.

The primary function of the *visual interface* (see Figure 13) is to display a 3D view of the surgical site, which is augmented with icons and text that provide supporting information regarding the status of the TP system. Animated simulation of the system can be displayed as a picture-in-picture, informing the surgeon of the robot status and activity. The *verbal interface* translates spoken surgeon commands into internal text strings, which are then analysed and acted upon. The *aural interface* augments the visual cues by providing audible cues and information to the surgeon. The *gesture-based interface* performs tool change between the SRS and the SNS automatically during surgery to relieve the surgeon from teleoperating this task and to perform it faster and more safely.

Results

The TP system was teleoperated successfully by a surgeon performing a demonstration of a bowel closure and shunt placement on a phantom with no human assistance. These accomplishments have resulted after resolving the system-development issues discussed in the following paragraphs. The surgeon was observed during the operation and interviewed after it to determine the effectiveness of the TP system and its user interface. In addition, timing measurements were recorded throughout the operation. The results of these observations and measurements are discussed in the section on Experimental observations and measurements, below.

Performance issues resolved by design approaches

Some performance issues were resolved through implementation of design approaches, as described below:

1. *Supply delivery*. ISSUE: the supply dispenser should store sterile surgical supplies that are inexpensively packaged and that can be opened and handled automatically by a robotic manipulator. APPROACH: thermoformed supply trays were designed that were sealed sterilely by continuous strips that could be opened when pulled by the robot.
2. *User interface*. ISSUE: the surgeon, while using both hands teleoperating a robot in the performance of a surgical task, needs to command the autonomous robots to perform supply-delivery and tool-changing tasks; hence, the surgeon cognitive overload should be minimized. APPROACH: speech, gesture and graphics interfaces (described above) were designed in such a way as to not distract the surgeon from the surgical tasks at hand. Unique protocols for tool changing and supply dispensing coordinated automatic interaction between the SRS and the SNS, while the SCS monitored and prevented impending collisions between these manipulators.
3. *Supply and tool tracking*. ISSUE: tracking of supplies and tools is necessary for recording the inventory of all the supplies in the surgical cell (including the patient). APPROACH: both RFID tag readers and machine vision were used to track the movement of supplies in and out of the surgical cell. The system maintained an updated inventory of all the supplies and tools in the operating room (which can be queried by the surgeon).
4. *Tool change*. ISSUE: the compliance of the SRS, typical for a surgical robot, complicates tool change because of the uncertainty in the robot's pose and the deflection induced when contacted by the SNS. APPROACH: a special autoloader mounted on the surgical arm (Figure 5) was designed, which is also capable of automatically loading tools that are placed close enough to the SNS.
5. *Collision avoidance*. ISSUE: as the robots converge into a small surgical site, they may collide. APPROACH: distal and slim end-effectors were designed for these robots as well as on-line collision avoidance algorithms.
6. *Medical record*. ISSUE: generating a medical record of a procedure is necessary to ensure continuity in subsequent stages of patient treatment. APPROACH: videos of events and vital signs were indexed in the order of the surgeon's commands. After a procedure is completed, relevant events can be selected, by browsing the procedure indexes, in order to form its record.
7. *Subsystems interfaces*. ISSUE: every TP subsystem, each developed by a different organization, needed to be integrated into the system as well as to operate as a stand-alone unit during recovery from an error. APPROACH: a flexible architecture was designed where

loosely-coupled subsystems communicate through high-level interfaces, including those with a remote human operator.
8. *Error handling*. ISSUE: errors may occur during a surgical procedure, in which case they need to be rectified. APPROACH: methods were developed for detecting errors while the system is performing a procedure. When an error is detected, the system transitions into a safe mode, from which it can be brought back to normal operation through the intervention of a remote system administrator.

Experimental observations and measurements

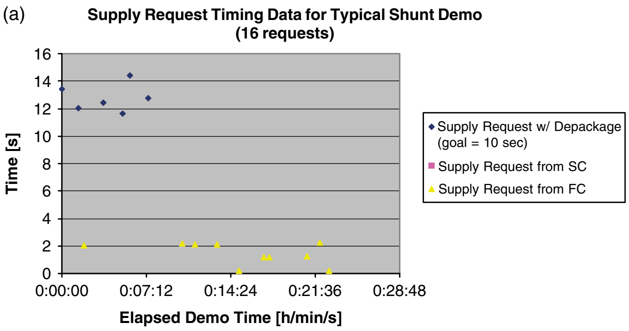
As stated above, a bowel-closure and shunt-placement procedure was successfully demonstrated on a phantom without the need for human assistance. The procedure lasted 30 min and was conducted by a surgeon with prior training in the TP system operation.

The time required for delivering a supply, including depackaging, was 12.7 s on average with a SD of 1 s (Figure 14). The time required for tool change was 14 s on average with a SD of 0.4 s (Figure 14). The average time required by a human operator to change a tool is about 30 s.

The user interface allowed effective control of the system, and no intervention from the user administrator was required. The interaction with the system felt 'natural' to the surgeon and allowed him to concentrate on the surgical tasks. The ability of the system to queue several commands averted interruptions during multiple tool changes or supply deliveries. In cases where a speech command was not understood by the system, the surgeon was prompted to repeat the command. In a few cases, the surgeon had to repeat a gesture when interacting with the SNS.

The small workspace of the SRS was temporarily occluded from the viewpoint of the surgeon when the SRS exchanged supplies with the SNS.

The supply count at the end of the procedure was accurate. A video of the procedure was recorded automatically, including time stamping and indexing of the commands issued by the surgeon during the operation.



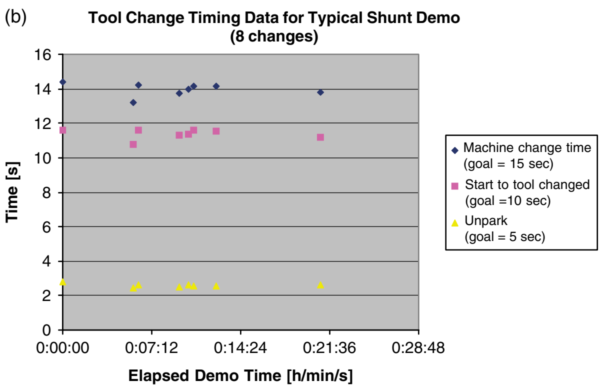


Figure 14. Time performance of the entire TP: (a) supply delivery time in typical procedure; (b) tool change time in typical procedure

Conclusions and Discussion

The goal of Phase I of this research program was to verify the feasibility of remotely conducting a robotic surgical operation, with no medical personnel in the surgical site. To meet this goal, the TP system was developed and used to demonstrate the feasibility of conducting robotic surgical operations by a remote (human) surgeon and the feasibility of automating some of the support functions in the operating room, such as changing tools or dispensing and tracking supplies.

Beyond its applicability to teleoperation, TP technology may change some aspects of current practices in the operating room: The use of surgical robots is becoming common and medical information and devices are proliferating. Interacting with each individual device and dealing with the large amount of information can be cumbersome and may lead to errors and lack of efficiency; the system demonstrated in this project provides an environment in which all the robots and devices are integrated through a layer of software which presents a unified information and control interface to the surgeon. Furthermore, operations requiring the coordination of several devices may be performed autonomously without the involvement of the surgical team. The concept of incorporating automation in the operating room may be implemented and lead to:

- Integrating all the medical devices in the operating room and enabling a single person to interact with them.
- Integrating imaging equipment and data with surgical robotic equipment to perform minimally invasive, image-guided procedures, such as intravascular interventions.
- Archiving and correlating relevant information and events occurring during a surgical procedure.
- Performing surgical procedures in remote locations where there are no medical personnel.

The lessons learnt from this research effort include the following:

(a) *Automation in the OR.* Where feasible and effective, certain human functions can be performed better (faster, more accurately and in a less costly manner) by robotic manipulators. Automation should be introduced into the operating room to alleviate the burden of low-level tasks and to reduce the bandwidth required for remote operation.
(b) *Medical device interfaces.* Each device in the operating room should be amenable to control by, and information exchange with, a computer as well as a human. This will allow full integration and central control of all devices but not impede the direct intervention of a human.
(c) *Robot features.* Although a surgical robot and a scrub-nurse robot perform different functions, they should have the following common features: minimal footprint and weight, sleek distal links, and safe operation around humans.
(d) *Diagnostics and error recovery.* In case of an error, the system diagnostics will require a human to make decisions or control the system remotely to recover from that error. Rather than trying to automatically recover from innumerable possible errors, the system should fall back to a safe mode and wait for human intervention.

There are many challenges that need to be overcome to perform trauma surgery with a robotic system:

(i) *Sterilization.* Cleaning and sterilization must be incorporated into the design of every subsystem. The ability to clean and sterilize the subsystems and sterilize them between operations is a critical function that is usually introduced by designing sterile barriers in which the part the part of the system that come in contact with the patient directly or via other components is removable and can be sterilized. The rest of the system that can not be sterilized is wrapped with a sterilized drape that include a sterilized barrier. To some extent this challenge was already met by several subsystems, such as the TRS, SRS and SDS. However, a systematic approach may be used to guarantee stability across the entire pod.
(ii) *Full surgical procedure.* In order to perform a full surgical procedure the system must be capable of performing exploration of the wounds, dissection, suction and irrigation, handling larger masses of tissue and supplies (e.g. lap pads). These tasks define the requirements for the surgical robot workspace as well as its capabilities to apply force and torque through its surgical tools.
(iii) *Anaesthesia.* Anaesthesia needs to be an integral part of a TP system, including the ability to handle and place intubations and intravenous lines.
(iv) *Number of manipulators.* It is recognized that multiple manipulators are required to perform and assist a wide variety of tasks that are necessary to complete a surgical procedure. The operation of multiple robotic arms presents fundamental challenges associated with collision avoidance and collaborative operations.
(v) *Robustness.* A complex system has many potential failure modes. Decreasing the failure rate and safely handling error conditions to recover operation is critical and challenging issue that effect the overall performance of the system.

In conclusion, TP demonstrated that there are many functions in the operating room that can be automated, while reducing the work load of low-level functions such as tool and equipment handling while allowing nurses to concentrate on high-level tasks. The results indicate that these low-level functions are conducted faster and more effectively by an autonomous machine than by a human. The results also demonstrated the feasibility of having a surgical robot interacting with autonomous manipulators to accomplish surgical tasks. Moreover, toward this goal it was shown that it is feasible to palletize the supply and surgical tools interfaces to be manipulated by autonomous robots in a cost-effective way. The combined autonomous and remotely controlled operation were enabled by a user interface that provided the surgeon with the appropriate level of situation awareness and control capabilities of the surgical site as well as the entire operating room. Beyond remote applications, a integrated system in which all the information, manipulators and imaging technologies work together seamlessly, and can be controlled by a consolidated interface, would present enormous benefits to current surgical practice.

TP demonstrated the ability of a robotic system that can perform some surgical procedures controlled by a remote surgeon and assisted by autonomous robots and devices. Future work may be focused on developing semi-autonomous platforms capable of performing life-saving procedures on a patient with limited access to human medical resources. For example, modules that can autonomously perform critical life-saving procedures with the supervision and assistance of a corpsman who may not have high-level medical skill. Miniaturization of the system, deployment in the field and operation during patient transportation may also be addressed in future work.

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