Raven-II: An Open Platform for Surgical Robotics Research

Blake Hannaford*, *Fellow, IEEE*, Jacob Rosen, *Member, IEEE*, Diana W. Friedman, *Member, IEEE*, Hawkeye King, *Member, IEEE*, Phillip Roan, *Member, IEEE*, Lei Cheng, *Member, IEEE*, Daniel Glozman, *Member, IEEE*, Ji Ma, *Member, IEEE*, Sina Nia Kosari, *Member, IEEE*, and Lee White, *Member, IEEE*

***Abstract*—The Raven-II is a platform for collaborative research on advances in surgical robotics. Seven universities have begun research using this platform. The Raven-II system has two 3-DOF spherical positioning mechanisms capable of attaching interchangeable four DOF instruments. The Raven-II software is based on open standards such as Linux and ROS to maximally facilitate software development. The mechanism is robust enough for repeated experiments and animal surgery experiments, but is not engineered to sufficient safety standards for human use. Mechanisms in place for interaction among the user community and dissemination of results include an electronic forum, an online software SVN repository, and meetings and workshops at major robotics conferences.**

***Index Terms*—Open source, research platform, surgical robot.**

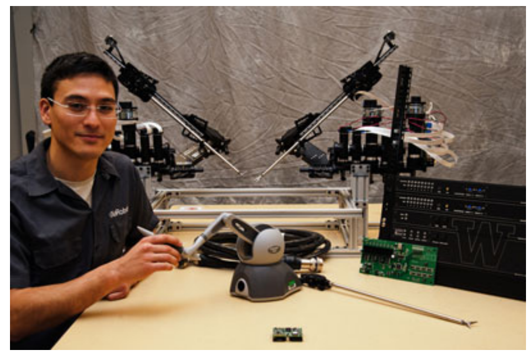

Fig. 1. Raven-II system including two arms, two instruments, and compact, rack-mount, electronics, and control unit. PC board seen in front of electronics is the high-speed USB 2.0 interface (two are used inside the amplifiers).

I. Introduction

ROBOTIC technology has made great inroads into the practice of surgery. Several successful companies, led by Intuitive Surgical Inc., have commercialized robotic devices for surgery. Due to the high value of surgical tasks, and their significant risks, robotic surgical devices make use of two types of control, both requiring detailed supervision or teleoperated manipulation by the surgeon. In the case of orthopedic bone-milling robots such as Robodoc [1] or Acrobot [2], a surgeon preplans the operation on preoperative images, assures that the patient and robot are properly prepared, fixated, and registered with preoperative images, and initiates a machine-tool like operation to prepare a bone cavity for insertion of an implant. In the other systems discussed later, the robot is directly teleoperated by the surgeon. Robot motion is directly slaved to the surgeon's hands, and no motion occurs unless a surgeon designates engagement.

This paper describes a new surgical robot platform, Raven-II[1], for research leading to improved performance and new capabilities relative to existing teleoperated surgical robots (see Fig. 1). Building on our earlier development of the first Raven platform in 2005 [3], the goals of Raven-II are as follows.

1) Provide hardware and software to support research innovations in surgical robotics.
2) Provide a common software and hardware environments so that research innovations can be shared and built upon.
3) Create a software environment suitable for high-level robotic functions such as motion planning, computer vision, and machine learning.
4) Embrace open standards as much as possible to facilitate integrating robotics research results from the larger robotics community.
5) Provide a robust hardware platform capable of sustained and rigorous evaluation experiments, including animal surgery.

It was not a goal of the project to create a robot with sufficient safety engineering for use on human patients. The purpose of this paper is to describe the opportunities for new collaborative surgical robotics research using the open common platform provided by Raven II.

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*B. Hannaford is with the Biorobotics Laboratory, University of Washington, Seattle, WA 98195 USA (e-mail: blake@uw.edu).

J. Rosen, J. Ma, and D. Glozman are with the Human Bionics Laboratory, University of California, Santa Cruz, CA 95064 USA (e-mail: rosen@ucsc.edu; jima@soe.ucsc.edu; daniel@glozman.org).

D. W. Friedman is with the Intuitive Surgical, Inc., Sunnyvale, CA 94086-5304 USA (e-mail: diana.friedman@gmail.com).

H. King, L. Cheng, S. N. Kosari, and L. White are with the Biorobotics Laboratory, Unviersity of Washington, Seattle, WA 98195 USA (e-mail: hawkeye1@uw.edu; leicheng@uw.edu; kosari@uw.edu; leewhite@uw.edu).

P. Roan is with the Robert Bosch LLC Research and Technology Center, Palo Alto, CA 94304 USA (e-mail: proan@uw.edu).

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[1]"Raven", "Raven-I," and "Raven-II" are trademarks of the University of Washington.

Literature: Since FDA approval of the da Vinci over 2200 systems are in place, and over 360 000 procedures were performed on humans worldwide in 2011. The da Vinci has been shown to decrease the risk of leak during bowel surgery [4] and to reduce the rate of injury during esophageal surgery [5]. The highest volume robotic-assisted procedure is nerve-sparing radical prostatectomy [6], [7]. Use of da Vinci in hysterectomy is rapidly growing.

Several recent workshops and a new technical committee of the IEEE Robotics and Automation Society have highlighted the need to improve the scientific rigor of experimental validation in robotics. Although more common in medical research, issues such as hypothesis driven experiment design and statistically significant results are infrequently described in the experimental validation of today's robotics research products.

One requirement for rigorous validation of algorithms and computational methods in robotics is sufficient reliability to allow enough experimental repetitions to achieve statistical power. The Raven-II design is based on the Raven-I prototype [3] which had an unusual amount of hardening, robustness engineering, and field testing under harsh conditions [8]. Raven-II is engineered to be reliable enough so that users will be able to generate robust results. Raven-I has already been used in animal experiments and has sufficient robustness for the rigors of such use.

Even though the da Vinci has dramatically enhanced the dexterity of laparoscopic procedures, the integration between computation and surgery is essentially unchanged from generations ago. In most robotic surgery today, use of computational tools, whether intelligent, networked, references to databases, or processing of images, is limited to before or after the procedure and is not supported on the robot system itself. Raven-II will enable a network of researchers to prototype-advanced surgical robotics devices, systems, and techniques, and evaluate them in realistic contexts including animal procedures. Besides new and less invasive treatments, such technology can provide easier access to care in remote parts of the U.S. and the developing world.

II. Raven-II System Description

A. Hardware

Raven-II hardware (see Fig. 1) has the following improvements over Raven-I.

1) Mechanism: The motor chassis (base) is the most extensively redesigned portion of the Raven-II [9]. There were two goals in this redesign of the Raven-I motor chassis, *first* to simplify the geometry, cable runs, and cable tension adjustments and *second* was to narrow the base so that two Raven-IIs could be mounted on either side of the surgery site, allowing for a total of up to four Raven-II arms to be applied to a single surgical field (see Fig. 2). A photo of the new design is shown in Fig. 3. The motors for axes 2–7 are arranged in a line. The width of the base was reduced from 225 to 120 mm.

The Raven-II tool interface is designed to facilitate research on new instrument and system designs. The mechanical interface specification is available to researchers on request from the authors. The interface consists of four spindles in a diamond

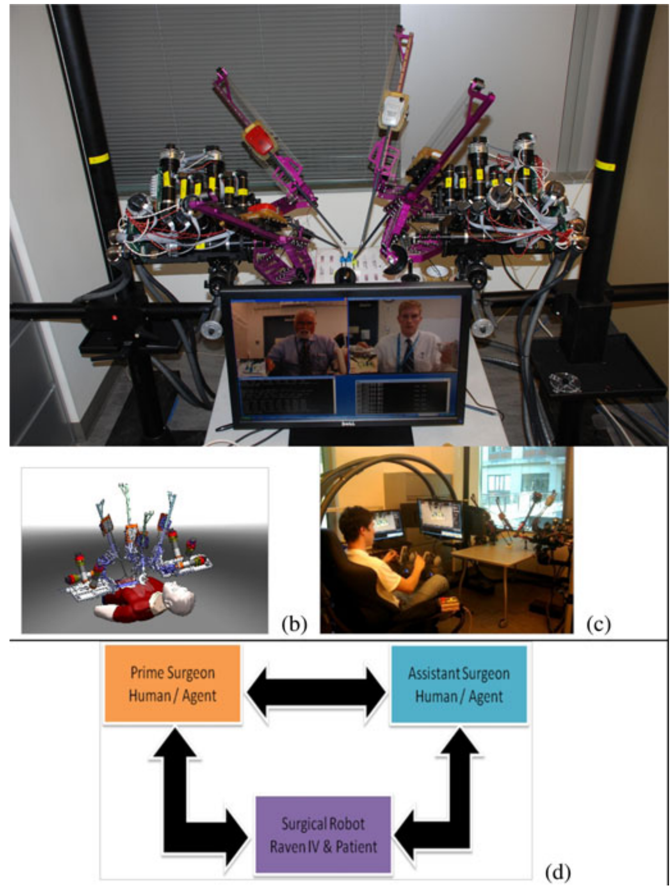

Fig. 2. Four Raven-II robotic arms and two cameras arranged for collaborative telesurgery. (a) Drs. M. Sinanan and T. Lendvay located at the University of Washington, Seattle collaboratively teleoperating the Raven-IIs located at the University of California, Santa Cruz; (b) CAD rendering of four Raven-II systems; (c) surgical console; and (d) block diagram of collaborative telesurgery.

shape configuration, each perpendicular to the long tool axis. A single spring-loaded release tab frees the tool from the interface. The tool attachment interface is smaller than that of da-Vinci but is not compatible as is with da-Vinci instruments.

2) Wrist and Instrument: The Raven-II system includes one removable tool, a grasper designed by Manuel Moreyra (U.S. Patent #6 969 385). The grasper (see Fig. 4) has 4 degrees of freedom (wrist roll, wrist yaw, and finger pitch times two fingers) and is 10 mm in diameter.

3) Kinematic Model:

a) Positioning joints: Link frames for the positioning joints (Axes 1–3) are related to the motion center and are shown in Fig. 5. There are differences between the left and right arm geometries and link frames are assigned slightly differently in left versus right arm.

In the above figure, La_{12} and La_{23} are the angles of the fixed mechanism links. For the Raven-II $La_{12} = 75^\circ$ and $La_{23} = 52^\circ$ (see Fig. 6).

b) Instrument joints: Link frames for the Raven-II grasper wrist (Axes 4–6) are the same for left and right instrument, since the instruments are identical (see Fig. 7). In Fig. 7, the instrument is shown from the top as if resting on a table with the spindles down and viewed from above. The two grasping jaws can be

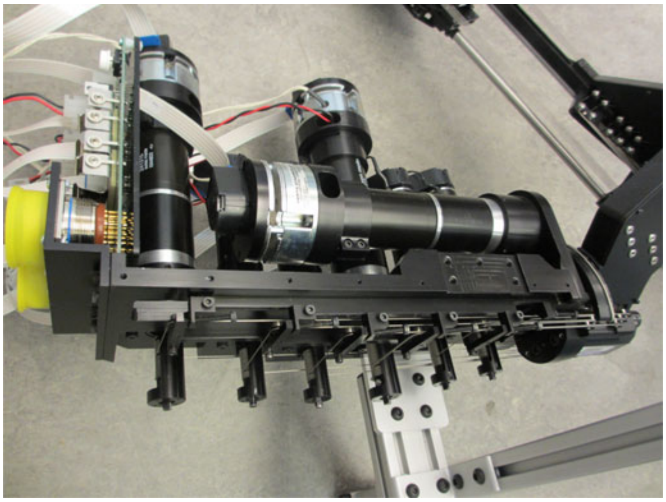

Fig. 3. Photo of the Raven-II motor chassis showing cable tensioners. Arranging six of seven motors in a linear array reduced the width of the base.

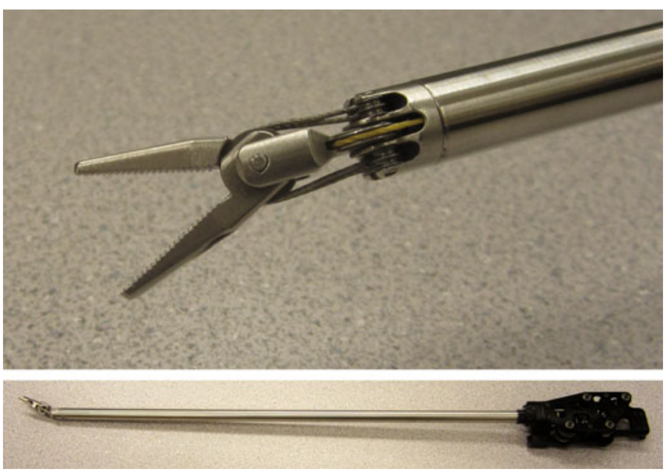

Fig. 4. Photo of the Raven-II instrument wrist designed by Manuel Moreyra.

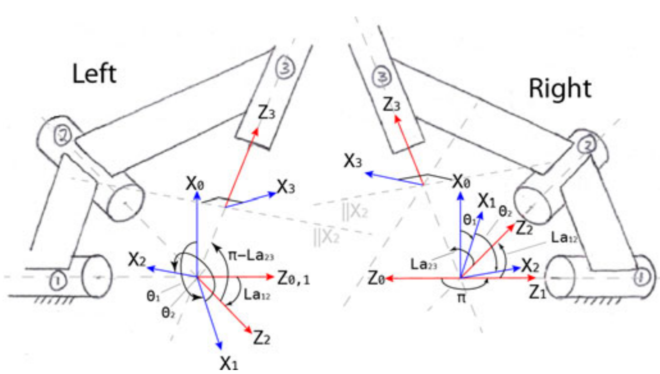

Fig. 5. Frame assignments for Frames 0, 1, 2, and 3.

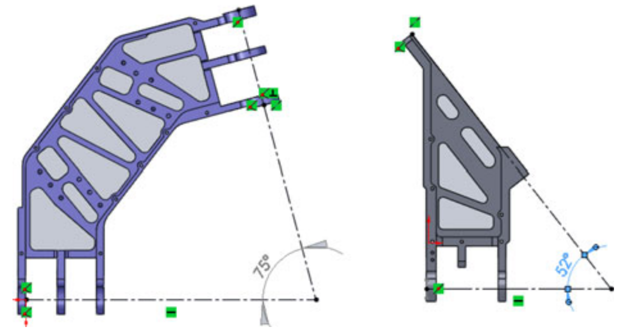

Fig. 6. Link angles are designated La_{12} (left figure, first link) and La_{23} (right figure, second link).

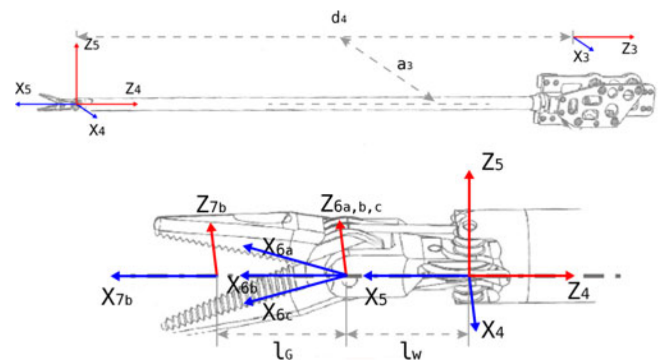

Fig. 7. Frame assignments for Frames 4, 5, 6_{abc}. Frame 6_b indicates a midpoint between the two jaws, and 7_b frame which can be used when the jaws are open prior to a grasp.

TABLE I
ARM PARAMETERS FOR THE POSITIONING JOINTS

Left Arm

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	La_{12}	0	0	θ_2
3	$\pi - La_{23}$	0	d_3	$\pi/2$

Right Arm

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	π	0	0	θ_1
2	La_{12}	0	0	θ_2
3	La_{23}	0	d_3	$-\pi/2$

TABLE II
INSTRUMENT PARAMETERS

i	α_{i-1}	a_{i-1}	d_i	θ_i
4	0	a_3	d_4	θ_4
5	$\pi/2$	0	0	θ_5
$6_{a,b,c}$	$\pi/2$	l_w	0	$\theta_{6a,b,c}$
7_b	0	l_G	0	0

analyzed as identical copies of link 6 and are treated the same in the kinematic model.

c) DH parameters (positioning joints): The Denavit Hartenberg parameters (using Craig's notation) for the left and right arms are given in Table I. d_3 represents the prismatic joint motion parallel to the instrument long (insertion) axis.

d) DH parameters (instrument joints): Frame assignment and DH parameters are the same for the left and right default instruments, and are given in Table II.

Note that a_3 is zero for the standard Raven-II graspers. When other instruments are used, a nonzero a_3 allows for an offset between the tool roll axis and the motion center. d_4 is a fixed tool length parameter relative to the standard Raven-II grasper which is zero for the initial Raven-II instrument of Fig. 4 and may be nonzero for future instruments.

e) Inverse kinematics: To our knowledge, the inverse kinematic solution is available in closed form only for the case where $a_3 = 0$. The instruments distributed with the Raven-II have $a_3 = 0$ and thus the closed form solution applies [10]. For future instruments in which $a_3 \neq 0$, a numerical method will be developed which is fast, accurate, and gives all solutions 100% of the time [11].

4) Electronics and Control System: Compared to Raven-I, the electronics have been dramatically reduced in size (a total of 5U of rack space by 8 in depth) and the number of cables has been reduced. The change from Raven-I's brushed to Raven-II's brushless dc motors enabled significant simplification of the power electronics and cabling.

5) Software: The software control system has evolved from the 1000-Hz hard-real-time teleoperation loop of Raven-I [3]. Servo control, including forward and inverse kinematics and feed-forward gravity compensation, is still based on a 1000-Hz real-time servo layer. The operating system environment has been changed to the standard Linux kernel with the CONFIG_PREEMPT_RT patch set. This allows the real-time software to run in user space and to include C++ (as well as C) code—both improvements in terms of ease of development.

A significant goal of the Raven-II software effort was to improve the ability to integrate a telerobotic surgery system with robotics research results from the greater robotics community.

We compared three potential software environments with which to improve the ability to develop and evaluate applications on Raven-II. The alternatives we considered were Robotics Operating System (ROS) [12], Surgical Assistive Workstation (SAW) [13], and the Image Guided Surgery Toolkit (IGSTK) [14]. Based on this comparison, we selected ROS for a middleware layer above our 1000-Hz servo layer code. The Raven-II control software is implemented as a ROS "node" (r2control).

6) Surgeon Interface: Currently, the PHANToM Omni (SenseAble Technologies) is used as the master device. The Omni features 3-DOF force-feedback and 6-DOF position/orientation sensors. The surgeon station also includes a usbconnected foot-pedal that enables and disables the surgical manipulator, allowing the surgeon to reposition (index) or put down the Omni styli without moving the robots. A graphical user interface allows surgeon login and parameter adjustment, and communicates slave state changes [15]. A new surgeon interface console featuring 3-D video, ergonomic seating, and haptic feedback to three fingered master devices on both hands is being developed and will be deployed at UCSC and UW [see Fig. 2(c)]. The surgeon interfaces and communicates with Raven-II using and efficient TCP/UDP prototcol over any distance covered by the Internet. The packet protocol is easy to adapt to other user interface systems [16].

B. Feature Summary

The key features of the Raven system are as follows.

1) Two seven-axis spherical manipulators with a remote motion center and 10-mm wristed instruments with compact drive mechanism and interchangable instruments.
2) Open hardware interfaces (at the tool interface and mounting bolt pattern, see Section III-B).
3) 1000-Hz real time control software distributed under the LGPL license (see Section III-B).
4) PLC-based safety processor for robust experimental (but not clinical) use.
5) Integration with the ROS open source robotic control library for easy interfacing with robotics software and programming models.
6) Open TCP/IP interface between user interface and robot, logging and access to all control signals.
7) A community of research groups using the Raven.

III. Research Network

The Raven-II system is currently installed at Harvard University (Prof. R. Howe), Johns Hopkins University (Prof. G. Hager), University of Nebraska (Prof. S. Farritor), UCLA (Prof. W. Grundfest), U.C. Santa Cruz (Prof. J. Rosen), U. C. Berkeley, (Profs. P. Abeel and K. Goldberg), and University of Washington (Profs. B. Hannaford and H. Chizeck). Each of these sites has clinical collaborators for their work with Raven-II. These systems were funded by NSF grant CNS-0958441. Five new systems are currently under construction for additional universities: University of Central Florida, University of Western Ontario, two systems for Montpellier University (France), and Stanford University. These systems are funded through contracts between these sites and the University of Washington with subcontracts to U.C. Santa Cruz.

A. Goals and Mechanisms

The Raven-II research network has the goal of advancing the state of software and hardware capabilities for surgical robotics. The key to achieving that goal is a set of mechanisms currently in use for sharing and collaborating on software. The collaboration mechanisms include the following.

1) An Internet Wiki containing technical information on the Raven-II system (https://brl.ee.washington.edu/−ravenIIwiki/index.php/Main_page).
2) Electronic blog for discussion of technical issues (http://r2db.tumblr.com/).
3) An online software repository for Raven-II source code.
4) Workshops currently being organized for major robotics conferences.

B. Open Source Terms

The Raven II software is released to Raven-II users under the Limited GPL (LGPL) license. The intent is that each user site will retain IP rights to their own contributions but share them freely within the community of Raven users for research purposes.

Hardware is open to modification of any kind. CAD files of the tool interface and the mounting bolt pattern are available to all users for research purposes. For example, anyone can design a new instrument or adapter which can work with the Raven system. As with software, all Raven-II users retain their own hardware IP with an expectation that they share designs among the users for research purposes.

C. Initial Steps and Use Cases

In January of 2012, the first eight sites received their Raven-II systems and they have initiated their research. The Raven-II at one site suffered shipping damage which has been repaired. The research consortium met at the ICRA 2012 conference in St. Paul MN on May 14, 2012, and distributed some tasks among the team including, resolving some issues with kinematic equations, design and prototype modifications for the tool and tool adapter to support sterilization for survival animal surgery, and developing a tactile sensor for the jaw tip. An ongoing series of such meetings, open to all, is planned for major conferences.

Online resources described earlier are currently available to all current and future Raven-II user sites. Raven source code can be released to researchers upon request to the authors.

A few hypthetical use cases will be described to illustrate the types of collaborations enabled by the open source robotic hardware model.

1) A small academic lab, under an early-career investigator, studies and develops a new instrument for robotic surgery. They develop a prototype using the mechanical instrument specification (see Section II-A1). Then they collaborate with a larger center for animal testing of the instrument on a Raven-II system. In a similar scenario, a large medical instrument company, develops a robotic instrument prototype in house, according to the Raven spec. Then, they collaborate with one university for animal testing and a second university for advanced control algorithms. Since both universities have Raven-II, the same prototype can be tested at both sites and the control results can be applied at the animal testing site.
2) Two computer science labs engage in a cooperative project to develop an advanced motion planner for surgical robotics. One of the labs has a Raven-II, and the other has an existing code base of ROS-based planners. The ROS-based planners are easy to integrate with Raven-II.
3) Extensive medical imaging capabilities are essential for image guided robotic procedures. A lab having medical imaging expertise can use state of the art and powerful packages such as OpenIGTlink [17] to easily integrate image guidance into the Raven Linux/ROS-based software control system.
4) Investigators can connect Raven II systems over the internet in novel ways to explore technically challenging future medical care delivery scenarios such as one or more expert surgeons at a central site, interacting with junior surgeons at different sites with the capability to share and trade control at the remote sites [16].
5) A control and dynamics researcher desires to test an advanced controller on a model of a medical robot. Using another ROS feature, the *rviz* 3-D visualization environment,[2] the control researcher can run their algorithm on a dynamic model of Raven-II which displays an animation of the robot. The 3-D model used to design and build the robot has been exported and adapted to the off-the-shelf ROS URDF and DAE descriptions of the robot. *rviz* then determines the pose and picture of the virtual system.

[2]`http://www.ros.org/wiki/rviz`

IV. Conclusion

The Raven-II is a platform for collaborative research on advances in surgical robotics. Seven Universities have begun research using this platform. By basing the software on Linux and ROS, we facilitate software development and mutual support from and within three communities: Linux, ROS, and surgical robotics research groups. We anticipate accelerated progress in surgical robotics research with the ultimate aim of better outcomes for patients.

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