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Open-Source Research Platforms and System Integration in Modern Surgical Robotics

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Abstract: In modern medical research and development, the variety of research tools has grown in the previous years significantly. It is crucial to exploit the benefits of shared hardware platforms and software frameworks in order to keep up with the technological development rate. Sharing knowledge in terms of algorithms, applications and instruments allows researchers to help each other's work effectively. This is a relatively new trend in the traditionally closed domain of Computer-Integrated Surgery, where community workshops and publications are now providing a thorough overview of system design, capabilities, know-how sharing and limitations. This paper overviews the emerging collaborative platforms, focusing on available open-source research kits, software frameworks, cloud applications, teleoperation training environments and shared databases that will support the synergies of the diverse research efforts in this area.

Keywords: surgical robotics, shared hardware platforms, software frameworks, cloud applications, teleoperation training.

1. Introduction

Medical robotics is one of the most rapidly developing fields of modern robotics, which is partly due to its competitiveness. The surgical robotics market is estimated to grow at an annual rate of 12% through 2018, reaching a size of $18 billion [1]. The manufacturers and developers consider these high-end hardware platforms and software programs the key assets of the research, protecting them in various ways (patents, industrial secrets etc.). Nevertheless,

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there is a growing need for open-source and easily accessible platforms and software/hardware solutions to facilitate future development in all fields of robotics. Various high-end robot controllers have already been available for such purpose, e.g. the Real-Time Application Interface (RTAI) for Linux platforms [2]. There has been a significant rise of open-source efforts in the field of Computer-Integrated Surgery (CIS), encouraging numerous key industrial stakeholders to support these efforts.

In medical robotics, due to the uniqueness and physical dimensions of hardware platforms, there is a lack of mobility and accessibility for most of the developers in the community. The sharing of program codes, toolkits and frameworks are usually carried out through online databases, granting access to the hardware through cloud-based control platforms. In the past decades, the concept of medical robotics has never been separated from the terms of telerobotics and teleoperation [3]. With the recent rise of cloud robotics, a promising perspective has appeared where not only the development and research, but the process of testing and operation could also be applied through cloud-based platforms. The aim of this paper is to provide a thorough overview into the emerging collaborative platforms, focusing on available open-source research kits, software frameworks, cloud applications, teleoperation training environments and shared domain ontologies for surgical robotics.

The paper is organized as follows: in Section 2, the most relevant medical robotics software platforms are presented. In Section 3, certain issues are discussed with the system-related application programming interfaces, addressing the research hardware environment in Section 4. Section 5 is dedicated to the da Vinci Research Kit, followed by a review of current community efforts and system integration in Section 6. The paper is concluded with a discussion and the projection of a future roadmap.

2. Software in medical robotics

In this paper, some of the open-source and free-to-use platforms and software solutions are discussed, where one has complete control over the software components, allowing program code customization and re-implementation. In most cases, there exists a wide community of developers, which continuously maintains, develops and updates the software. The most important of these open-source platforms are listed below.

2.1. 3D Slicer

3D Slicer[1] is the most popular and most widely used open-source, free software package that can be used for visualization and image analysis, particularly for medical imaging [4]. The software was designed to be natively available for multiple operation system platforms, including Windows, Linux and Mac OS X. 3D Slicer is operated based on the NA-MIC kit and other software components [5]. These include the Visualization Toolkit (VTK) and the Insight Segmentation and Registration Toolkit (ITK), which will be discussed later in this paper. The modularity of the Slicer 3D is shown in *Fig. 1*. Both research and clinical projects employ the 3D Slicer for applications, such as brain tumor removal [5] or prostate biopsy, using the OpenIGTLink robotic platform [7]. The 3D Slicer has a remarkable flexibility and connectivity to other software platforms, such as the Open Core Control software for surgical robotics [8]. Besides visualizing the actuator positions in a given application, *virtual fixtures* (control boundaries for safety that should not be crossed during an intervention) can also be specified.

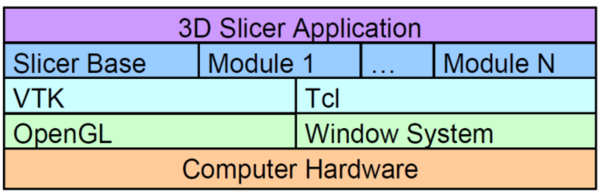

Figure 1: The modularity of the 3D Slicer [4].

2.2. Visualization Toolkit

The Visualization Toolkit[2] (VTK) is a free toolkit, its primary use includes image processing, visualization, 3D volume rendering and scientific visualization [9]. Due to the object oriented design, other modules can be integrated into the software for modification and expansion purposes [10]. VTK includes a C++ class library and other interpreted interface layers, such as Tcl/Tk, Java and Python.

[1] http://www.slicer.org/
[2] http://www.vtk.org/

2.3. Insight Segmentation and Registration Toolkit

Similarly to the VTK, the Insight Segmentation and Registration Toolkit[3] (ITK) is an open-source, cross-platform system, mostly used in segmentation and image registration problems [11]. ITK includes a vast collection of biomedical image analysis that was created within the framework of Visible Human Project [12]. ITK is also used by 3D Slicer, as a component.

2.4. Computer Integrated Surgical Systems and Technology

Computer Integrated Surgical Systems and Technology[4] (CISST) is an extended collection of libraries, a useful tool for many CIS and medical robotics applications. The function and libraries are used by e.g. the Surgical Assistant Workstation[5] (SAW), a cross-platform framework based on C++ for device integration in computer assisted intervention applications. CISST supports interchangeability, therefore all the devices that meet the basic requirements are interoperable with each other. The requirements for interchangeability are based on two main restrictions imposed by the use of *commands*: 1) parameters must be derived from a base type, and 2) a finite number of signatures are supported [13].

2.5. Image-Guided Surgery Toolkit

The Image-Guided Surgery Toolkit[6] (IGSTK) was created to support the development of image-guided applications, where intra-operative tracking is also possible [14]. The main features of the IGSTK toolkit include [15]:

- reading and display of medical images,
- interface to common tracking,
- GUI and visualization capabilities,
- multi-scale axial view,
- four-quadrant view (axial, sagittal, coronal or 3D),
- point-based registration,
- robust common internal services for logging, exception-handling and problem resolution.

[3] http://www.itk.org/
[4] https://www.cisst.org/
[5] https://www.cisst.org/Saw
[6] http://www.igstk.org/

2.6. Medical Imaging Interaction Toolkit

The Medical Imaging Interaction Toolkit[7] (MITK) is an open-source software system for development of interactive medical image processing software. MITK combines the VTK and ITK toolkits with several customized interactive components [16]. The versatility of the hardware platforms is increased due to the combination of these elements. The software system can be extended with additional modules e.g. the built-in interactive image segmentation.

2.7. Public Software Library for UltraSound

The Public Software Library for UltraSound[8] (PLUS) is a software platform written in C++ and built on the NA-MIC Kit [17], [18]. PLUS contains library functions and applications, supporting tracked ultrasound image acquisition, calibration and processing. The software package is equipped with numerous tools that are related to ultrasound data processing, extended with the support of optical and electro-magnetic trackers or other imaging devices [19].

2.8. National Alliance for Medical Image Computing

The National Alliance for Medical Image Computing[9] (NA-MIC) is an interdisciplinary team of medical experts, software engineers and computer scientists, developing new computational tools for medical image data visualization and analysis. Therefore, the NA-MIC kit is not standalone software, but rather a collection of methodologies and tools [20]. Numerous software packages are integrated in this kit, such as the 3D Slicer, VTK and ITK.

2.9. Surgical Assistant Workstation

The main purpose of the Surgical Assistant Workstation (SAW) is to integrate different components of a robotic surgical system, using and reusing the elements in the system structure, as shown in *Fig. 2*. Developed by the Johns Hopkins University, SAW supports the most common tools of CIS, such as tracking systems, stereo viewers, haptic devices, and other common hardware platforms, including 3D Slicer, various medical research robots and the da Vinci master console and robotic arms, created by Intuitive Surgical Inc. [21]. SAW is written in C++ and the research was founded by the National Science

[7] http://www.mitk.org
[8] https://www.assembla.com/spaces/plus/wiki
[9] http://www.na-mic.org/

Foundation[10] (NSF). Thanks to the high level of modularity, SAW can be extended with new components in many research systems. The easy connectivity among multiple devices allows one to integrate them into a sophisticated surgical system. An example was demonstrated by JHU by integrating a snake robot with the da Vinci console for laryngeal surgery [22].

2.10. The Common Toolkit

Common Toolkit[11] (CTK) supports biomedical image computing, licensed under Apache 2.0. The toolkit can be used for academic, commercial and other purposes free of any restrictions. The main scope of the current CTK development efforts includes the *DICOM*, *DICOM Application Hosting, Widgets* and *Plugin Framework* [23].

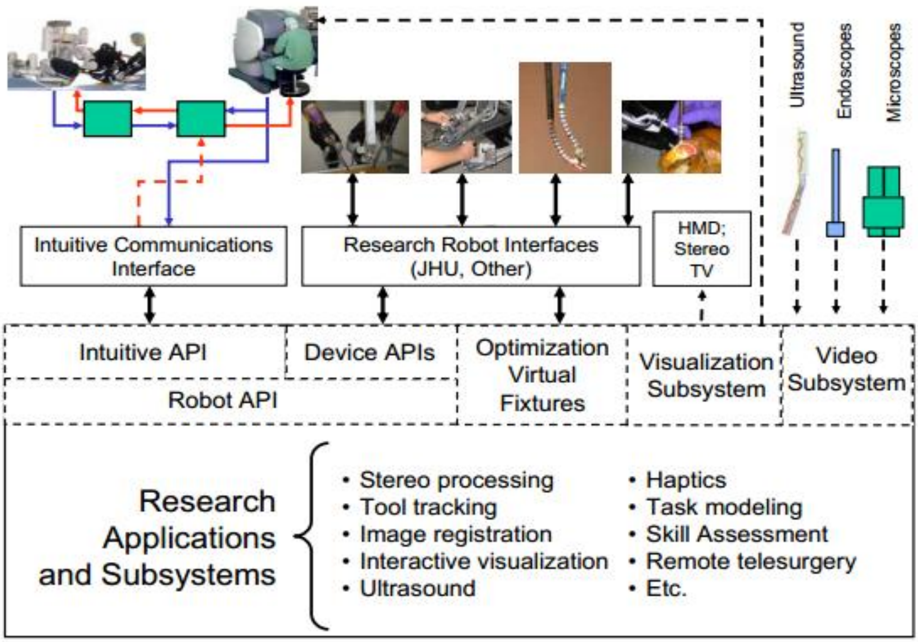

Figure 2: Architecture and capabilities of the Surgical Assistant Workstation [22].

10 http://www.nsf.gov/
11 http://www.commontk.org/

2.11. The NifTK

NifTK[12] is a translational imaging platform combining various toolkits developed at the Centre for Medical Image Computing (CMIC), University College London (UCL). These toolkits include the NiftyReg, a collection of programs to perform rigid, affine and non-linear registration for medical images; the NiftySim, a solver for non-linear elastic or viscoelastic deformation; the NiftyRec, a software package for fully 3D Stochastic Emission Tomographic Reconstruction; the NiftySeg for image segmentation; and NiftyView, a cross-platform graphical user interface providing an entry point to the above mentioned packages. The NifTK is widely used in rigid instrument tracking and computer aided surgery planning [24].

3. System-related APIs

In general, the academic community aims for the development of generic development bits, supporting a wide range of components and devices, such as the examples listed in Section 2. However, some manufacturers have recently developed particular Application Programming Interfaces (APIs) for various systems, such as Medtronics' intra-operative navigation platforms, which features a StealthLink research interface [25], or the OpenIGT Link connection with the KUKA Sunrise controller and 3D Slicer [26].

Today's most deployed surgical system, the da Vinci Surgical System[13] (Intuitive Surgical Inc., Sunnyvale, CA) is not provided with open access by default. Data cannot be retrieved from the robot, programs and components are not subject to change and one cannot extract any information about the basic operation principle, mostly due to liability issues. Limited amount of information can be recorded using various data collection tools [27]. In some cases, the manufacturer allows access to previous generations of their systems, which become transparent by the provided open-source software [28].

4. Research hardware environment

On closed systems, it is fairly difficult to conduct fundamental research, for obvious reasons. Therefore, in order to achieve technological development, some of the manufacturers grant partial accessibility to their closed systems. In the case of the da Vinci, there exists a real-time stream of kinematic and user event data from the robot that can be read, provided by the de Vinci Application

[12] http://cmic.cs.ucl.ac.uk/home/software/
[13] http://www.intuitivesurgical.com/

Programming Interface. It is important to mention that the total replacement of certain components, such as the controller body, can transform the da Vinci system into and open-source platform.

Raven II is one of the most successful open-source robotic platforms. Developed at the University of Washington and supported by DARPA[14], the Raven II became the greatest competitor of the da Vinci system [28]. Furthermore, with the help of the National Institutes of Health[15] (NIH), 8 robots have been created and distributed to European and North-American locations. Currently, the Raven II research platform can be purchased from Applied Dexterity Inc.[16] The platform operates based on the Robot Operating System (ROS) architecture.

5. The da Vinci Research Kit

The da Vinci Research Kit (dVRK) is one of the most capable research platforms in surgical robotics. In fact, the kit is a collection of retired, first-generation da Vinci robot components and tools, provided with additional open-source control electronics and software.

5.1. Hardware components

The dVRK contains the components listed below:

- Two da Vinci Master Tool Manipulators (MTMs),
- Two da Vinci Patient Side Manipulators (PSMs),
- A stereo viewer,
- A foot pedal tray,
- Manipulator Interface Boards (dMIBs),
- Basic accessory kit.

The research kit contains the original, unmodified mechanical components, therefore it is possible to transform a da Vinci Classic system into a research kit, although some of the components are not available for researchers due to their commercial use. In the dVRK hardware set, the Endoscopic Camera Manipulator (ECM) is not included along with several other components from the original system, but the lack of these elements is not a major issue from the development point of view. In general, for research purposes, the control electronics and control software are the most essential parts of the system.

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[14] http://www.darpa.mil
[15] http://www.nih.gov/
[16] http://applieddexterity.com/

Recently, a novel, open controller platform was created by JHU, Worchester Polytechnic Institute (WPI) and their partners [30]. The source files of the control electronics were also published online. The research platform is equipped with an IEEE 1394a Firewire interface, capable of maintaining a communication speed of 400 Mbit/sec. In order to achieve a satisfactory degree of security and reliability, it is crucial to create real-time communication between the devices in the system. The control box includes two FPGA modules and two Quad Linear Amplifiers (QLA), as shown in *Fig. 3*. The assembly described above is capable of driving and controlling a single robotic tool. Two da Vinci Master Tool Manipulators (MTMs) and two da Vinci Patient Side Manipulators (PSMs) can be controlled using four sets of control electronics, requiring a total of 8 pieces of FPGAs and QLAs. The integration of the dVRK to a retired, fully operational da Vinci robot is shown in *Fig. 4*.

The da Vinci Research Kit is based on the centralized computation and distributed I/O architecture [31]. The main advantage of this structure is that there is only one control electronics that maintains contact with the peripheral inputs and outputs, allowing the central computer unit to perform the calculations, located at the control units. In general, the central unit is a Linux-based computer with some real-time component expansion.

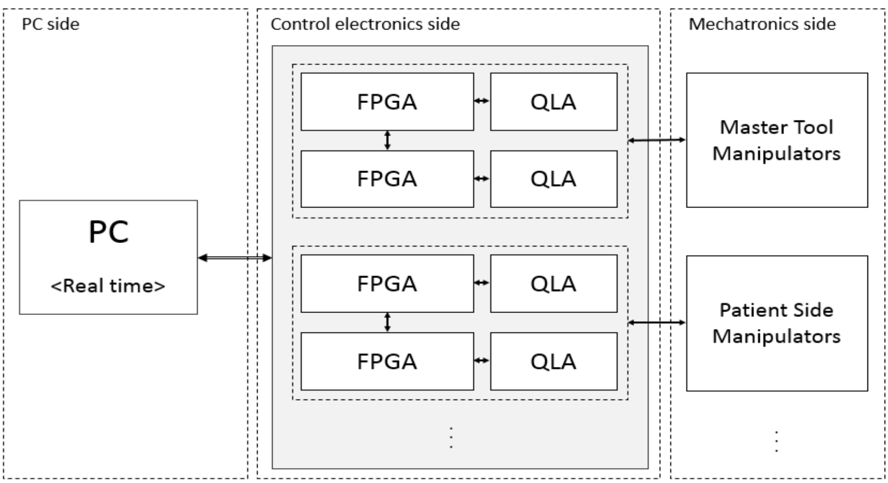

Figure 3: Schematic representation of the hardware structure Workstation [32].

5.2. Low level software architecture

The FPGA module firmware is available online[17] and published under a BSD license, therefore it can be freely modified. The RT-FireWire is one of the best approaches to solve the real-time communication between the subsystems over Firewire, while the communication implementation is achieved through standard Linux C++ libraries [33].

The PC-side operating system is preferably Linux-based, as there exists a real-time extension (RTLinux), a Linux OS that runs under the supervision of a hard real-time microkernel [34]. The software architecture, as a whole, can be divided into five *functional layers* (I-V) and three *development layers* (A-C) [35]. The functional layers, implemented on the PC side, are stratified by the complexity of their function, while the development layers are sorted by the programming language complexity they use. The open-source property is extensively supported by the previously described SAW and CISST libraries, allowing the system to be used as a completely open research platform.

Figure 4: The da Vinci Surgical System and the da Vinci Research kit. System components: Patient Side Manipulators (left), the dVRK controller (middle) and the Master Tool Manipulators (right).

[17] https://github.com/jhu-cisst/mechatronics-firmware/wiki/FPGA-Program

6. System integration and current community efforts

The integration of the above mentioned systems to real hardware applications has become a widely researched and published topic recently. Beside the development and testing of the available systems, new interface standards are also created, in order to achieve a reliable closed-loop control and synchronization. The OpenIGTLink is an open-source network communication protocol that defines a messaging protocol for data transfer, primarily focusing on images, commands and joint positions [36]. Since its introduction in 2008, several use cases, actual and potential roles of the OpenIGTLink have been presented [37]. One of the use cases focuses on an MRI-compatible manipulator for prostate biopsy, where three major components were equipped with OpenIGTLink interfaces: a 3T MRI scanner, a planning and navigation software and an MRI-compatible needle placement robot [38]. Other use cases include an MRI-compatible manipulator for stereotactic neurosurgery, an open interface of lightweight robot system and a robot for transrectal ultrasound guided brachytherapy. One of the greatest advantages of the OpenIGTLink platform is the simple design and the multi-platform C++ software library, allowing the users to minimize the engineering effort, facilitating multi-site and academic–industrial collaborations while enabling transition from research to clinical use.

6.1. Use cases

There are a great number of ongoing research projects involving the dVRK, mostly focusing on the master and slave side manipulators and the vision system. One of the limitations of the da Vinci Surgical System is the difficulty of the simultaneous operation of the patient side manipulators and the stereo vision system, decreasing the efficiency of the surgical interventions. To overcome this issue, the Novel Master Interface (NMI) and the Controllable Vision System (CVS) were developed at the Seoul National University, Korea [39]. The evaluation and validation of the system's clinical applicability, peg task experiments are in progress. The NMI is a wireless communication interface including a multidirectional switch, a Bluetooth module, an encoder and a button cell battery. The multidirectional switch is mounted on the patient side manipulator, as shown in *Fig. 5*. The multidirectional switch sends data to the CVS through the Bluetooth module in real-time, controlling the camera position of a novel camera holder hardware interface.

Figure 5: The NMI structure: (a) front side, (b) back side, (c) NMI attached on the MTM.

Another setup for the da Vinci laparoscopic camera handling was developed at Óbuda University [40]. A low-cost, lightweight Computer Assisted Laparoscopic robot arm (CALap) was primarily created for surgical training purposes, which was extended with the Apollo classicalbox trainer [41]. The CALap hardware is based on a mechanical structure created using aluminum profiles, extended with additional gears and 3D-printed parts. The software design follows the master–slave concept, having high level programming and low level electronic handling approach. This allows one to integrate the setup into the dVRK system.

In the past years, the Robot Operating System (ROS) has become an essential part of robotic research and industry. The large set of libraries and tools facilitates the integration of different robot components on a single platform. To interface the dVRK with ROS, a CISST–ROS stack was developed, which allows the dVRK to communicate using ROS messages [42]. The interface has been tested through several use cases, such as an augmented reality-based 3D measuring application, motion planning framework for surgical assistance, learning by observation for surgical subtasks and satellite servicing. The latter is addressing a non-medical robotics application, such as refueling spacecrafts in on-orbit scenarios [43].

7. Conclusion and future roadmap

The da Vinci Research Kit is one of the greatest breakthroughs in the field of open-source surgical robotic research and development, which is mostly due to the direct access to an actual clinical system, even though these systems are retired and out-of-date. As of May, 2015, there are 17 dVRK research teams operating around the world, maintaining an active community through meetings and workshops. Particularly in Europe, several actions and projects (EuroSurge[18], I-SUR[19], ACTIVE[20]) have given a boost to synchronized robotics

[18] http://www.eurosurge.eu/eurosurge/

research, mostly founded by the EU Commission. IEEE Robotics and Automation Society[21] has also contributed to the generalization of surgical robotics through study groups, and there are initiatives for forming workgroups for surgical robotics ontologies. A great impact on the entire research field is expected, where more and more attention is to be given to open-source research instead of strictly commercial development.

The effectiveness of surgical robotics will evidently become higher with the use of open-source platforms and software. This paper reviewed the most widely-used, currently available software and hardware research platforms, aided with some highlights to the features and recently realized projects they supported.

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