

**Title:**

Prototyping a Hybrid Cooperative and Tele-robotic Surgical System for Retinal Microsurgery

**Authors:**

Marcin Balicki, Tian Xia, Min Yang Jung, Anton Deguet, Balazs Vagvolgyi, Peter Kazanzides, Russell Taylor.

**Johns Hopkins University, Baltimore MD 21211.**

**Abstract***Purpose*

This paper presents a tele-robotic microsurgical platform designed for development of cooperative and tele-operative control schemes, sensor based smart instruments, user interfaces and new surgical techniques with eye surgery as the driving application.

*System*

The system is built using the distributed component-based *cisst* libraries and the Surgical Assistant Workstation framework. The system includes a cooperatively controlled Eye Robot, a da Vinci Master manipulator, and a stereo visualization system with information overlays. We use constrained optimization based virtual fixture control to provide Virtual Remote-Center-of-Motion (VRCM) and haptic feedback.

*Application*

Such system can be used in a hybrid setup, combining local cooperative local control with remote tele-operation, where an experienced surgeon can provide hand-over-hand tutoring to a novice user. In another scheme, the system can provide haptic feedback based on virtual fixtures constructed from real-time force and proximity sensor information.

**Introduction:**

Vitreo-retinal surgery is the most technically demanding ophthalmologic discipline. It addresses common sight-threatening conditions including retinal detachment, complications from diabetes, macular pucker, macular hole and removal of retina-associated scar tissue. In current practice, retinal surgery is performed under an operating stereo-microscope with free-hand 20-25 gage instrumentation. In most cases, three incisions in the sclera (sclerotomy) are required: one for infusion to control the intra-ocular pressure, one for fiber-optic "light pipe" and one for a surgical instrument. The surgeons often operate in bimanual fashion with a "light pipe" in one hand and a forceps, laser, vitreous-cutting probe, fragmenter, aspiration, or another type of tool in the other hand. A typical vitreoretinal surgical task is peeling epiretinal membranes from the surface of the delicate retina. Another task which is considered to difficult but very desirable is cannulating 100um diameter retinal vessels for targeted drug delivery. Surgeons strive to overcome many human and technological limitations that include physiological hand tremor, poor visualization of surgical targets, and lack of tactile feedback in tool-to-tissue interactions.



Figure 0. Left: Surgeon operating. Right: Forceps and light pipe Instrument inside the eye.

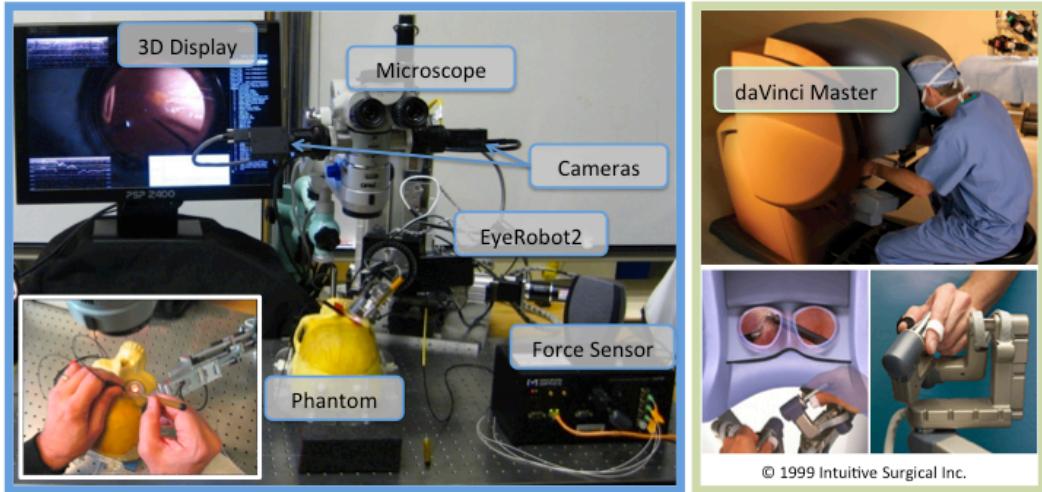
We address these challenges in a systems-based approach, creating the Eye Surgical Assistant Workstation (eyeSAW) platform for development and testing of micro-surgical robots, intra-operative sensors, human-machine interaction, robot control methods and new surgical procedures with vitreo-retinal surgery as the driving application.

Robotic manipulators are inherent part of the system and can provide the needed stability and precision. Although there are numerous robotic eye surgery concepts, we used two for this work. One type is the cooperative control robot like the EyeRobot2(ER2) where the surgeon and robot share the control of the surgical instrument [Uneri]. The main advantage is that the operator interaction with the surgical instruments is familiar and direct but much steadier than freehand operation and that the surgeon can remove the tool from the eye at any moment, without delay. This is very important in cases where the patient is locally anaesthetised and awake, and can move unexpectedly.

Another type is a tele-operation system where the surgeon controls the robotic manipulator from a remote master console [mitsubishi & das], most known example is the da Vinci Surgical System®, from Intuitive Surgical, Inc. a commercially available and clinically approved tele-robotic system for Minimally Invasive Surgical procedures (MIS). This system has similar advantages of minimizing hand tremor, but can be provide even finer degree of tool control by employing a motion scaling scheme. There are few disadvantages including difficulty in performing safe gross motion outside of the eye due to lack of visualization, significant reliance on correct definition of the location of the remote-center-of-motion mechanism that prevents excessive motion of the eye by constraining tool motion to intersect the sclerotomy incision location, and the increased slave design complexity to comply with stringent safety requirements.

We believe that incorporating these two paradigms into a single hybrid tele-robotic and cooperative system will combine the advantages and supplement the weaknesses found in the respective standalone systems. In this paper, we present a prototype of such tele-robotic surgical system, including overall architecture, EyeRobot2 and daVinci Master manipulators, and visualization, and various user interaction modes that incorporate tele-operation, cooperative control, and real time sensing information.

# System Overview

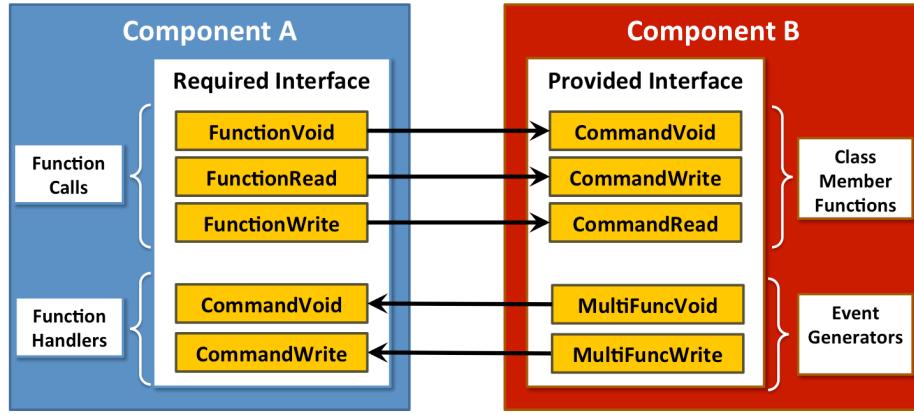


**Figure 1:** Devices in Telerobotic System: slave side display with EyeRobot2, and the daVinci Master Console.

## **System Architecture**

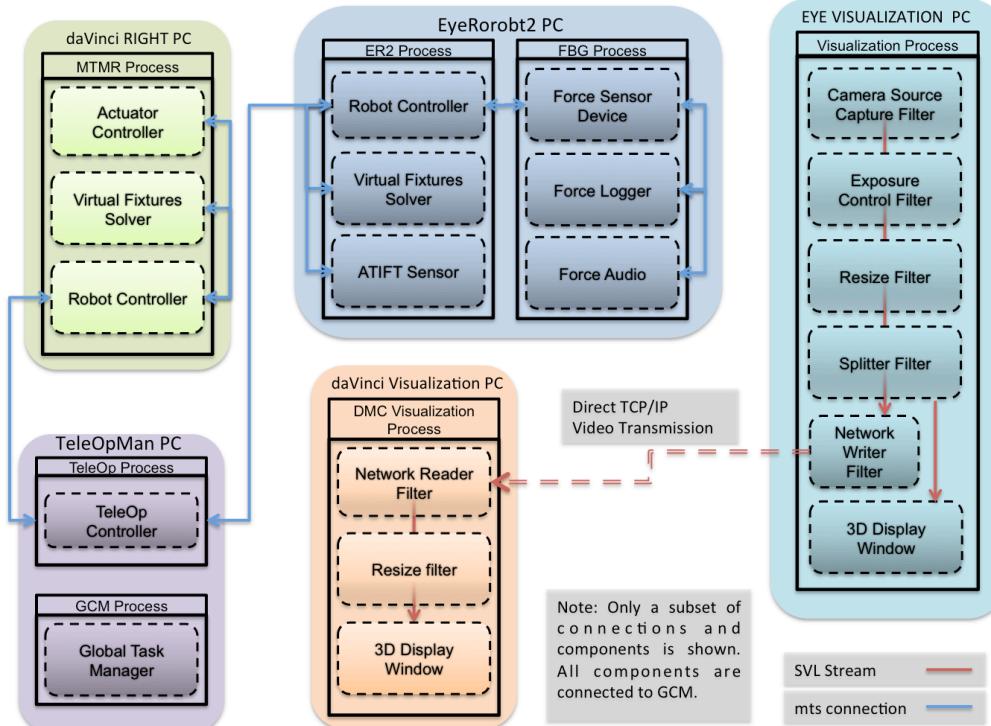
The eyeSAW relies heavily on the concept of component based system design by which new surgical system configuration and functionality can be rapidly prototyped with minimal or no modifications to existing devices and applications. The *cisstMultiTask* library provides this underlying component-based software framework. It supports two different architectures, multi-threaded architecture that has optimal performance for robot control applications and multi-process or distributed architecture that is scalable and extensible. The same programming model [Min-IROS10] allows these two architectures to be seamlessly and flexibly combined together to build a system with minimal source code changes at the user level. The connection and coordination of components in a system is managed by the Global Component Manager (GCM) which is unique to the system and defines system boundary.

The basic building block is a software component which has a list of standard commands contained in provided and required interfaces. The component (A) needs specific functionality has a *required interface* that is connected to another component (B)'s *provided interface* which provides that functionality. Upon connection, a component A can initiate a command which executes B's function or receives an event command from B. One advantage is that B can be swapped out for another component/device (C) that supplies a matching provided interface required by A. When the components are in the same process, the command execution is just a standard function call. In the case when the components are distributed over a network, a typical round trip execution of a command over a multi-hop network is 300 $\mu$ s with a payload of 150 bytes, which, for most applications, is an acceptable execution time.



**Figure 2.** Component Interface Connections.

Using the above framework we have created a slave-master tele-robotic surgical system that uses existing devices and their component software interfaces. A new component was added to host the teleoperation algorithms. To facilitate visualization



**Figure 3.** eyeSAW hardware view schematic with connections.

### da Vinci Master Console (DMC)

Through a collaboration agreement, we have acquired the mechanical subsystem, which includes two Patient Side Manipulators (PSM) and a daVinci Master Console (DMC) unit, comprising of two Master Tele-Manipulators (MTM) and stereoscopic display system. Each MTM is a cable driven 7-DoF serial robot with a redundant wrist mechanism. Our custom system allows for joint level control, so we can implement haptic force feedback, which is not available on the commercial system.

We want to use intra-operative sensing, from OCT or force sensors, to generate virtual fixture (VF) motion constraints that help the surgeons to perform a task. Virtual fixture are task-dependent motion constraints for a robotic manipulator performing a task by limiting its movement into restricted workspace and/or influencing its motion along a desired path and are classified as Forbidden Region (FRVF) or Guidance (GVF) virtual fixtures, respectively. VF primitives such as stay above a plane, move along a line, and rotate about a point can be combined using different operators to provide assistance for complex surgical tasks. We implement VFs using the constrained optimization formulation below, where  $C(X(q+\Delta q), X_d)$  is the objective function associated with the difference between the actual state variable  $X$  and the desired state variable  $X_d$ . The state,  $X = X(q+\Delta q)$  is a function of joint variables  $q$  and joint incremental motion  $\Delta q$ . The solution vector  $\Delta q_c$  must satisfy motion constraints in the form of one or more inequalities  $A(X(q + \Delta q)) \leq b$ . In addition, we make use of constraints involves  $\Delta q_U$  and  $\Delta q_L$ , the upper and lower rate limit for  $\Delta q$ . For each control step, the optimization controller computes a desired incremental motion  $\Delta q_c$ , based on constraints and objectives generated from various real-time input sources [ref: ankur's paper]

$$\begin{aligned} \Delta q_c = & \min C(X(q+\Delta q), X_d) \Delta q \\ \text{s.t. } & A(X(q + \Delta q)) \leq b, \Delta q_L \leq \Delta q \leq \Delta q_U \end{aligned}$$

We also implement bilateral feedback. When the slave encounters a force in the environment, (e.g, obstacle), it lags behind the command position and the user haptically feels this resistance, as the bilateral feedback objective acts to minimize the daVinci master and eyeRobot tracking error, by opposing the user's input motion on the daVinci master.

### (ER2)

The Eye Robot2 is a cooperatively-controlled robot assistant designed for retinal microsurgery. In cooperative control the surgeon and the robot both hold and control the surgical instrument simultaneously. The ER2 can assist during high-risk procedures, by incorporating virtual fixtures to help protect the patient, and by eliminating physiological tremor in the surgeon's hand during surgery. It is a 5-DOF serial manipulator with a XYZ stages for the base and two rotary stages that create a mechanical Remote Center of Motion (RCM). The user "drives" the robot by manipulating the tool which is attached to a 6-DOF force sensor. Like the MTM above, the control software is based on *cisst* library, complies with *cisstSAW* framework, and uses the Control Optimization framework to calculate incremental joint motions. Its high level control loop runs at 250Hz and commands the motion controller running at 1kHz (Gallil DMC1886 PCI). We have also design a line of robot compatible smart surgical instruments that have embedded micro-sensors. These provide direct real-time feedback to the robot which uses this information, if needed, to affect the surgeon's movements to prevent undesirable collisions with the retina, limit forces applied to the delicate tissues, or intuitively guide the surgeon to a particular target in the eye.

### Visualization

Currently, video is the sole feedback modality for the surgeons operating inside the eye. In creating a tele-robotic setup we required a video stereo-microscope system, with low latency, high frame rate, (high resolution, and high dynamic range) with Ethernet based communication for long range telecasts. Therefore, we have developed a high performance visualization sub-system built using *cisstStereoVision* library (SVL). SVL provides a wide array of highly optimized *filters*, such as capture device interfaces, image processing, network transmission functionality, overlays and video formatting for stereo-specific displays. The library is highly multi-threaded, adopting the GPU streams concept, where each filter in the pipeline has access to a pool of threads to process the latest video frame. The configuration of these filters in a pipeline is simple, allowing for rapid prototyping of various display architectures, e.g tele-operation. Figure x shows the such applications linked by TCP/IP network connection.

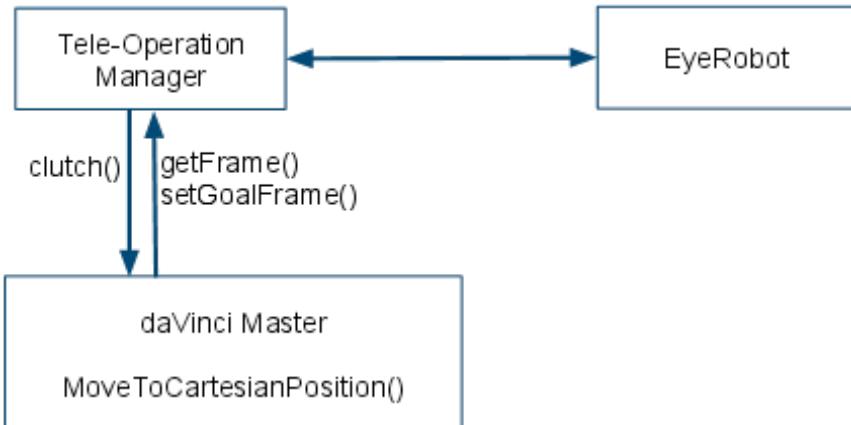
The slave system's visualization comprises a standard ophthalmological surgery stereo-microscope (Zeiss OPMI-MD) outfitted with two IEEE-1394B capture cameras (Grasshopper by Point Grey Research) each capturing 1024x768 pixels resolution images at 45 FPS. The left and right video stream is interlaced and on a passive 3D display (PSP2400 by Panorama Technologies) which separates left/right lines using passive polarized glasses. The capture and display latency is a few frames, on a modern multi-core Linux OS workstation. The stereo video stream is also split, encoded with lossy jpeg compression, and sent using *NetworkWriter Filter* (TCP/IP) over 1Gbit Ethernet to the master's display subsystem.

The master's visualization application running on an older multi-core windows XP machine, uses a very similar SVL pipeline but the video source is provided by the *NetworkReaderFilter*. This video stream is formatted for DMC's two display CRTs, at 1024x768 pixels per video channel. The display console itself is very ergonomic allowing the optimal alignment of visual and motor axes and offering excellent stereopsis. The final display frame rate is about 25FPS, with barely noticeable but insignificant delay of about 4-5 frames.

#### Tele-Operation Manager (TOM)

The TOM is a central component responsible for configuring, monitoring the state and high level control of the master and slave components. It also performs position offset computation and clutching. A typical TOM control loop queries the robotic manipulators for latest Cartesian pose via standard MTS interfaces (e.g., *GetFrame(mtsFrm4x4)* command), computes the next desired pose and executes a command that sets the goal position on the robotic manipulators: *SetGoalFrame(mtsFrm4x4)*. The robots run their own high frequency control loops that servo the robot to the desired pose, which can be inverse jacobian, or inverse kinematics methods. The TOM also provides a Qt based GUI that allows the operator to change the teleoperation method, and the workspace motion scaling between the daVinci Master and the Eye Robot.

- block diagram showing:



**Figure 4.** Schematic of teleoperation. Figure of the main components and the data types being exchanged. Also function

### Control Schemes and Applications

The flexibility and inherent functionality allowed us to quickly prototype a variety of control schemes that extend the functionality of the system beyond the sum of its parts. The two robots and TOM, utilize the robot control constraint optimization framework to calculate incremental joint motion based on system state and given task constraints, eg. force sensor information. Here are a number of control schemes we have implemented.

Classic **unilateral teleoperation (UTO)**, currently used by the daVinci system, does not include force feedback and the operator is required to close the control loop via the visualization system. This method works sufficiently for simple tasks but it lacks fidelity for more complex maneuvers or when visualization is poor and the operating environment is not allowing the slave to follow master, resulting in tracking error.

To diminish effects of inherent human hand tremor and enable more precise maneuvers found in micro-surgery, **motion scaling (MS)** was implemented. MS in a tele-operation system involves scaling the cartesian position of the master by a factor relative to the cartesian position of the slave.

In **bilateral teleoperation (BTO)** control the behavior of the slave is fed back into the master controller, and vice versa. If the slave motion is impeded by the environment, the motion of the master manipulator will also be impeded, pragmatically creating a sense of force-feedback. It is important to note that the EyeRobot2 has only 5DOF of control, so even though the tele-operation algorithm is commanding 6DOF Cartesian position and orientation, the desired rotation about the tool axis is omitted by the ER2 control optimizer.

The BTO control scheme is compatible with **virtual fixtures (VF)** [jake abbott] such as the virtual RCM (vRCM) where the tool motion is constrained so the tool shaft always intersects a single point in robot workspace, eg. trocar inside the sclera. The vRCM is implemented on the slave side and inherently reflected back to the master controller via the BTO logic. Since vRCM constrains the motion of the tool to 3 DOF there are a few ways to operate the master side. One way is to implement standard BTO on the master side, and another is to only consider the Cartesian translation of the master (operator is free to rotate the master joystick without affecting the slave) to drive the Cartesian position of the tool tip within the eye.

We have also created **dynamic virtual fixtures** on the slave manipulator by incorporating real time sensor information embedded in surgical instruments [Balick,Uneri]. One example is micro-force sensing, where interaction forces measured at the tool tip are virtually scaled up through cooperative control. Since the BTO involves position-position exchange the operator on the master side will experience this scaled force reflection.

The intuitive “hand-over-hand” control interface of the EyeRobot is very effective in general setup tasks of gross positioning the tool near the surgical site, aligning it for insertion through the sclerotomy trocar, or adjusting the position of the vRCM relative to the eye. These tasks are especially difficult in case of pure tele-operation due to lack of macro-field visualization not provided by the microscope. In our system, a technician can quickly position the robot to the desired site, and the surgeon can “clutch-in” with the master, and at any time, take over control with BTO. The BTO can provide very fine positioning for a specific task, especially when used with motion scaling. Furthermore, we have developed a controller located on the slave side, that considers both the master’s desired motion through BTO, as well as the desired motion of the ER2 operator. This **hybrid tele-operation and cooperative control** (HTCC) enables both operators to contribute to the control of the slave manipulator, while complying with any motion constraints, such as vRCM. Depending on the task, it may be more advantageous to have one operator use hands-on control of the slave to prepare for a maneuver and seamlessly “transfer” the control to an operator on the master side to perform the delicate maneuver with finer motion-scaled manipulation. Further, the level of contribution from the two inputs does not have to be equal. By adjusting the relative gains, one of the operators can be the dominant operator. Such control scheme could become a valuable educational tool, where the trainer directly guides the trainee through common surgical tasks.

### **Conclusions and Discussion:**

The process of developing this tele-operation system has shown that component based software architecture is very convenient for multi-device system prototyping and development. The resulting system is functional and can easily be adopted to accept new devices or to fit other applications, such as micro-vascular surgery, or neuro-surgery. For example, the daVinci master can be replaced with the Phantom Omni (SensAble Technologies Inc) to control EyeRobot2’s tool tip while inside the eye with haptic feedback of the 3DOF. Similarly, in the next iteration of the system we will add another EyeRobot and the other master manipulator to construct a bi-manual tele-operation system.

The actual process of development with *cisstMultiTask* was very smooth. Occasionally, additional component interfaces needed to be built, or existing ones extended. The debugging and testing of new modes of operation was efficient due to the ability to disconnect and reconnecting specific components/processes without restarting every process in the system.

Despite the slight latency, the tele-visualization system has sufficient frame rate for development purposes. Since our video capture application can handle 1600x1200 px resolution, the system is compatible with newer daVinci master consoles containing higher resolution displays, with none, or minimal compromise in performance. The bottleneck is the video codec processing which will be redesigned in the future. It is especially needed improvement for cases when the master and slave are separated by great distances, and the network delays are becoming significant. Long distance tele-operation will also require the transmission of audio.

Since EyeRobot2 was designed for pure cooperative control it does not have an actuated tool rotation axis or the ability to open/close instruments on its own. As is, it can be used with axisymmetric

instruments surgical pick, or illumination guide; but for use with more sophisticated tools it will be upgraded with a new tool actuation mechanism, that will allow for tele-operation of all available degrees of freedom the surgical instrument.

Currently, the operator of the master console indirectly experiences the dynamic virtual fixtures located remotely on the slave manipulator through standard bilateral teleoperation feedback. In order to provide a higher fidelity feedback for the master console operator, the master can create virtual fixtures locally using real time sensor information collected by the slave system.

Generally, the introduction of robots into the surgical flow adds to the operation time, a disadvantage outweighed by the benefits that they provide. From practical point of view, **hybrid teleo-operation and cooperative control**, can overcome a problem conventional tele-robotic concept applied to eye surgery: patient motion. This is especially problematic since most of operations patient is awake and locally anesthetized.

- For example, the operator of the EyeRobot can assess patient state and anticipate a sneeze...
- Fatigue might be decreased with teleop

The ultimate goal of the eyeSAW project is to enable more surgeons to perform currently impossible treatments and improve the safety and success rates of existing vitreoretinal procedures. With tools provided by the cisst/SAW infrastructure we can quickly progress to towards that goal.

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