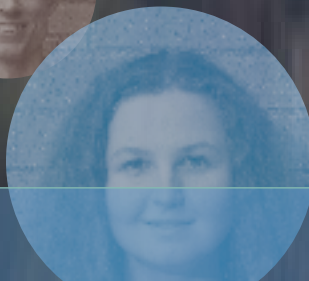
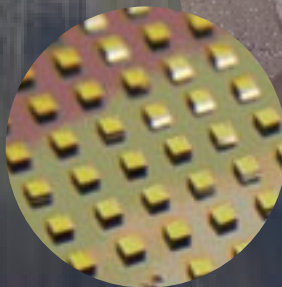
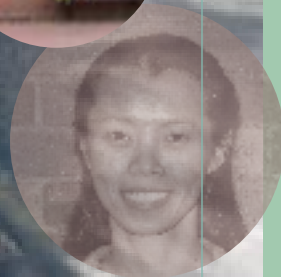
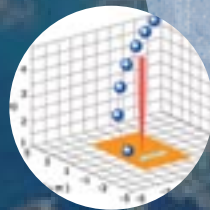
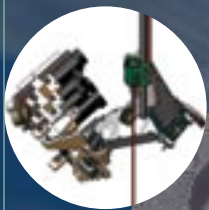


Electrical Engineering Kaleidoscope

# EEK 2006

A PUBLICATION OF THE ELECTRICAL ENGINEERING DEPARTMENT UNIVERSITY OF WASHINGTON  
ANNUAL RESEARCH REVIEW



# Markov Models to Perform Clinical Skills Assessment

THOMAS MACKEL, GRADUATE STUDENT (EE)

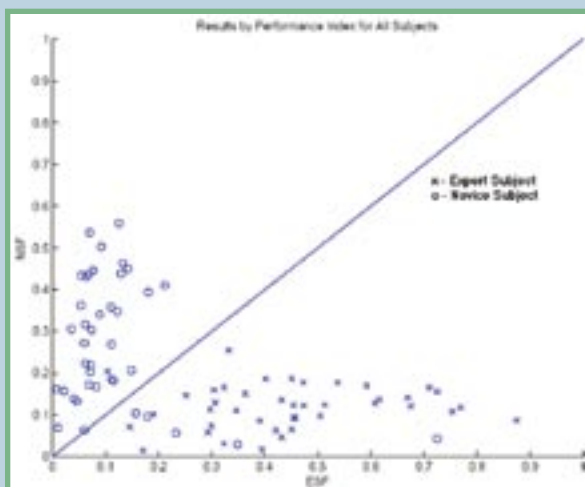


**Inspired by an analogy between medical procedure and spoken language, Markov Models were used to classify subjects using the E-Pelvis simulator (Stanford) with 92% accuracy. Certain model aspects revealed information about the medical procedure's "grammar," which will help develop a more compact model representation and a generalized methodology.**

Complicated medical procedures are a series of less complex sub-procedures, like "tying a knot," or "cutting tissue." These sub-procedures are a series of even more simple gestures, and gestures are a series of specific measurable forces. Forces (syllables), gestures (words), sub-procedures (sentences), and procedures (paragraphs) form the basis of the "language" of medical procedure.

Starting with force data obtained from experts performing an actual medical procedure, each continuous value data point is quantified to 1 of 32 discrete states, which are referred to as "syllables." This is analogous to each syllable having many different possible "pronunciations." A model of the expert data consists of the frequency of all expert syllable transitions, and the mean and covariance of the pronunciations associated with each syllable. A similar model is created from novice force data.

Force data taken from an unclassified subject is then used to make a third model, like the above two. Comparing the unclassified subject's model to the expert model yields an "Expert Skill Factor (ESF)," which represents how closely the subject's performance matched the performance of the aggregate of expert subjects. A Novice Skill Factor (NSF) is determined as well. Plotting the ESF vs. NSF shows a quantitative comparison of skill, referred to as the Performance Index, for multiple subjects.



SKILL FACTOR PLOT SHOWING THE CLASSIFICATION RESULTS OF 82 SUBJECTS. THOSE ON THE TOP LEFT OF THE DECISION BOUNDARY ARE CLASSIFIED AS NOVICE, WHILE THOSE TO THE BOTTOM RIGHT ARE EXPERTS. THE ACTUAL SKILL LEVEL OF EACH SUBJECT IS REVEALED AFTER DETERMINING THE RESULT.

This skill assessment technique is heading towards handling larger dimensional data with many more syllables, as well as extending the number of classes beyond two. Another possible direction is to work on identifying "words" and "sentences" of the procedure, and using this information to simplify the models.[EE](#)

FACULTY ADVISOR: PROFESSOR JACOB ROSEN  
COLLABORATORS: PROFESSOR BLAKE HANNAFORD (EE)  
RESEARCH AREA: SURGERY  
GRANT/FUNDING SOURCE: US ARMY MEDICAL RESEARCH AND MATERIEL COMMAND

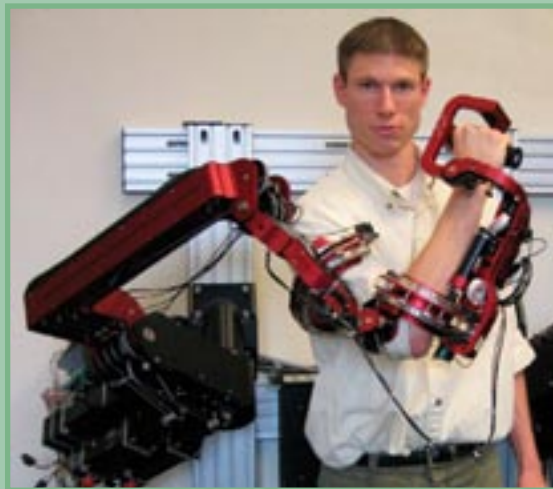
# Development of a 7 DOF Upper-Limb Exoskeleton

JOEL C. PERRY, LEVI M. MILLER, GRADUATE STUDENTS (ME)  
BOBBY DAVIS, GRADUATE STUDENT (EE)

An exoskeleton is a wearable external robot with joints and links corresponding to those of the human body. Through the use of gravity compensation, the exoskeleton supports the weight of itself, the human arm, and externally applied loads while the human controls its motion through neural inputs using surface electromyography-based (sEMG-based) or impedance-based control algorithms.

As a proof of concept for neural control (sEMG), two prototypes of exoskeleton arms were developed. The first prototype produced a single-joint (elbow) exoskeleton controlled by sEMG signals from the bicep and tricep muscles. The second prototype included two additional degrees of freedom at the shoulder.

The current seven degree-of-freedom (DOF) exoskeleton, serving as a wearable robot, is composed of seven cable-driven aluminum links.



THE 7 DOF EXOSKELETON ARM IS CONNECTED TO THE USER AT THE THREE INTERFACE POINTS: THE HAND, FOREARM, AND UPPER ARM. INTERFACE CONTACT FORCES, JOINT POSITIONS, AND SEMG SIGNALS ARE USED TO CONTROL THE ROBOT AS A NATURAL EXTENSION OF THE OPERATOR'S ARM.

Complex pulley arrangements transmit torques from motor space to joint space. Shoulder and elbow transmissions are implemented with two-stage pulley reductions, while wrist joint transmissions use single-stage planetary gear reductions followed by single-stage pulley reductions. Proximal placement of motors effectively minimizes weight and inertia of moving segments whereas distal placement of pulley reductions maximizes transmission stiffness.

An underlying gravity compensation algorithm is used to cancel gravitational effects while a higher-level control law is used to calculate additional desired joint torques. Contrary to most gravity compensation implementations, no known position trajectory is fed to the controller, eliminating the possibility of correcting steady-state errors through feedback. As a wearable robot that is physically attached to the human body, the exoskeleton naturally follows the operator's command. Using a muscle modeling approach with myoprocessors as its core elements, the system predicts joint torques from sEMG signals while using an impedance control law.

Among the exoskeleton's potential applications, the proposed control strategy will enable persons with neuromuscular impairments to improve and potentially regain upper-limb function and mobility. Potential applications that will be further studied include rehabilitation and automatic physiotherapy, as well as using the exoskeleton as a haptic device while generating force feedback in virtual reality environments. EE

FACULTY ADVISOR: PROFESSOR JACOB ROSEN  
COLLABORATORS: PROFESSOR BLAKE HANNAFORD (EE), DR. STEPHEN BURNS (REHAB. MED.)  
RESEARCH AREA: CONTROLS AND ROBOTICS  
GRANT/FUNDING SOURCE: NATIONAL SCIENCE FOUNDATION



# Next Generation Robotic-Assisted Surgery

MITCHELL LUM, KENNETH J. FODERO II, H. HAWKEYE I. KING,  
GANESH SANKARANARAYANAN, GRADUATE STUDENTS (EE)  
DENNY TRIMBLE, GRADUATE STUDENT (ME)  
GINA DONLIN, CLINT BLAND, UNDERGRADUATES



**Surgical robotics will revolutionize the way in which surgical intervention is performed. The integration of robotics and medicine will ultimately lead to better patient care. Less invasive procedures, more precise motion control, and quicker healing times are just a few of the potential benefits.**

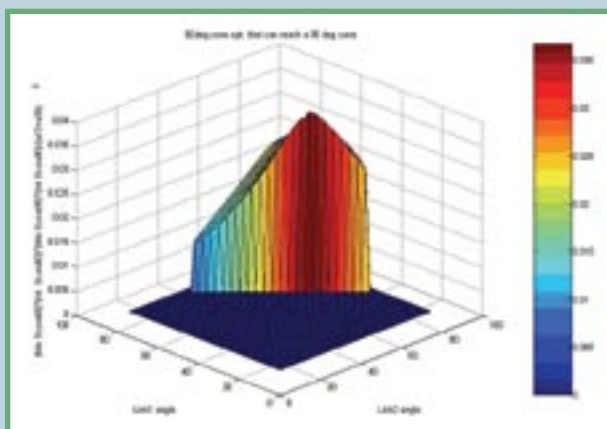
The first generation of surgical robots made a significant step toward integrating robotics and medicine. However, some of these systems were large and overbuilt. The BioRobotics Lab (BRL) is working on the next generation in surgical robotics. Primary electronics and a mechanism optimized for the requirements of minimally invasive surgical (MIS) procedures are in place. The BRL is currently working on control software, teleoperative control design, and user interfaces for local and remote control. As the field of surgical robotics continues to evolve, it is important to keep patient safety in mind. A safety control architecture is being developed that is aimed at moving an experimental system in the direction of intrinsically safe operation.

This project is part of the “operating room of the future” vision in which the patient is the only person in the room and doctors teleoperate robotic manipulators to perform surgery. The BRL Surgical Robot is being developed by an interdisciplinary team with members from the departments of surgery, electrical engineering, mechanical engineering, bioengineering and computer science. This surgical robot, which is currently a prototype undergoing testing, is composed of a number of subsystems. It is a two arm, 7-DOF, cable-actuated surgical robot system for performing minimally invasive telesurgery. Using a multidisciplinary approach to design the system will lead to a seamless integration into the operating room of the future.

MIS utilizes long slender tools and a video camera inserted through ports in the patient. Operating about this pivot point makes a spherical mechanism a natural candidate for a MIS robot manipulator. Using in-vivo MIS kinematic and dynamic data as a foundation, an optimization was performed to determine the ideal link angles for the 2-R spherical linkage. The dexterous workspace (DWS) is defined as the workspace in which surgeons spend 95% of their time, and the extended dexterous workspace (EDWS) as the workspace required to reach all the target anatomy in the human abdomen. Kinematic analysis of the 2-R spherical mechanism led to the derivation of the forward and inverse kinematics as well as the Jacobian matrix.

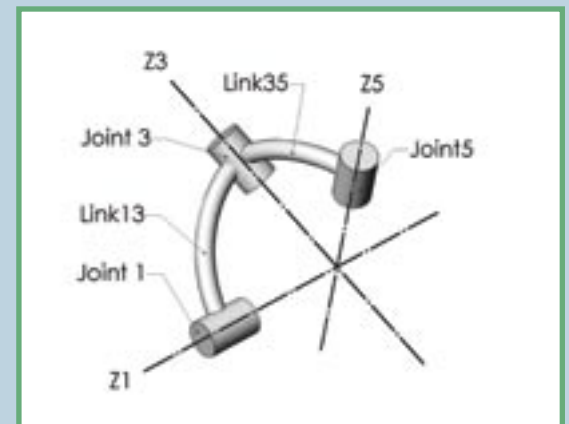
Isotropy is a measure of how well a manipulator can move in any arbitrary direction and is defined as the ratio of highest to lowest singular value of the Jacobian matrix. This score is unbounded, so isotropy is redefined as the ratio of the lowest to highest singular value to obtain a bounded scoring criterion that ranges from 0 (singular) to 1 (perfectly isotropic). There is an isotropy score associated with every pose of every design.

In order to perform an optimization over the design space, all combinations of link angles ranging from 16°-90° were analyzed with respect to isotropy. For each potential target workspace, the isotropy score is integrated over the workspace then multiplied by the minimum score within that target workspace. This provides a measure of average performance as well as penalizing target workspaces near singularities. The best target workspace score for each design candidate is then divided by the sum of the link angles cubed to provide a penalty for greater mass and inertia. The optimal manipulator is defined as the design of the highest composite score when scored against the DWS, but can also reach the entire EDWS. The resulting design for a 2-R spherical mechanism optimized for MIS yielded link angles of 75° and 60° (Link1 and Link2 respectively). These parameters were the basis for the mechanical design work required to bring this system to fruition.



DESIGN SPACE SCORE AS A FUNCTION OF LINK ANGLES.

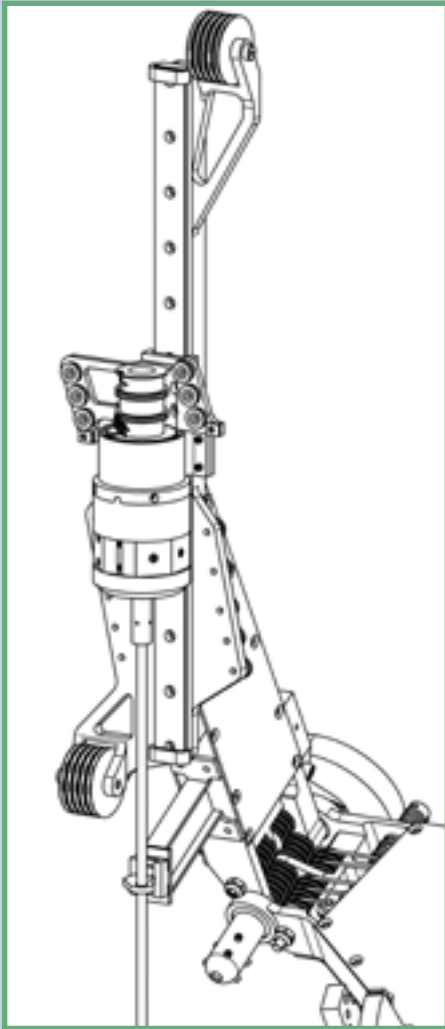
SPHERICAL MANIPULATOR, LINK AND FRAME ASSIGNMENTS.



The first four joint axes of the robot intersect at the surgical port location resulting in a spherical motion about the incision point that allows for tool motion just as in manual MIS. DC brushless motors mounted to the base of the surgical manipulator actuate all motion axes. Maxon EC-40 motors with 12:1 planetary gearboxes are used for the first three axes, which see the highest forces. Maxon EC-32 motors are used for the remaining axes. Maxon DES70/10 series amplifiers drive these brushless motors. The motors are mounted on quick-change plates, allowing for motor removal without the need for disassembling the cable system. The first three axes have power-off brakes to prevent tool motion in the event of a power failure.



THE BRL 7-DOF SURGICAL MANIPULATOR IS A CABLE-ACTUATED SYSTEM WITH ALL OF THE BRUSHLESS ACTUATORS MOUNTED ON ITS BASE. LINKS WERE OPTIMIZED BASED ON IN-VIVO MIS DATA COLLECTED ON PORINCE MODELS AS WELL AS HUMAN MEASUREMENT. THE COMPLETE SYSTEM INCLUDES TWO ARMS, WITH THE CONTROL SOFTWARE RUNNING ON AN RTAI LINUX COMPUTER.



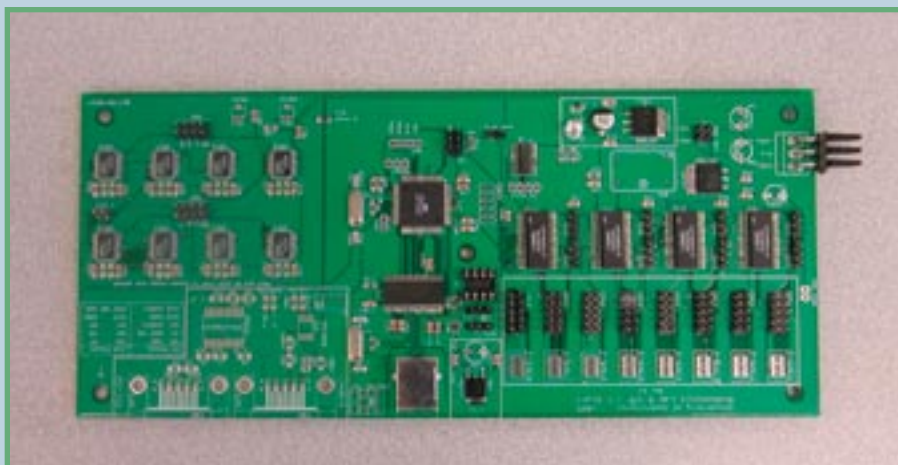
A CAD SHADED IMAGE OF THE SURGICAL ROBOT. CABLE ACTUATED WITH MOTORS ARE MOUNTED ON A STATIC BASE. THE COMPLETE SYSTEM WILL FEATURE TWO MIRROR IMAGE DESIGNED ARMS, ONE FOR EACH OF THE SURGEONS HANDS, PLUS A CAMERA HOLDING/POSITIONING ROBOT.

A CAD LINE DRAWING OF THE SECOND LINK AND TOOL INTERFACE BOX OF THE SURGICAL ROBOT. THE TOOL INTERFACE FEATURES QUICK RELEASE TOOLS THAT SUPPORT BEING INTERCHANGED DURING SURGERY BY A 'SCRUB NURSE ROBOT' TOOL CHANGER.

The control software is running on Linux with real-time extensions to the kernel (RTAI). The controller is implemented as a kernel module and RTAI grants it exclusive access to system resources, turning a full-featured application on Linux into an embedded-type system with highly accurate timing. The robot control loop runs at 1kHz.

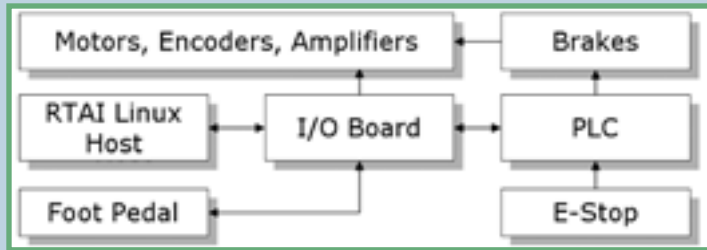
Well-defined software interfaces to the controller allow high-level control of the robot (start, stop, control gains, test inputs, etc) from the Linux host and surgical control by a master device across a network. The master device can be any suitable, high fidelity haptic interface; currently the Phantom Omni from Sensable Technologies is used. The surgeon interface also uses touch screen controls and foot pedal for user-friendly operation during surgery.

Connection between the robot and the Linux host is through a USB 2.0 I/O board also developed in the BRL. Custom drivers allow the board to communicate with RTAI Linux in USB 2.0 bulk transfer mode. This USB board is designed to be highly versatile and includes a variety of inputs and outputs, including 8 24-Bit Encoders, 8 16-Bit DACs and 8 General Purpose I/O Pins. PC control software can set DAC values output to the DES 70/10s controlling motor torques, or read encoder values to get the robot joint positions.

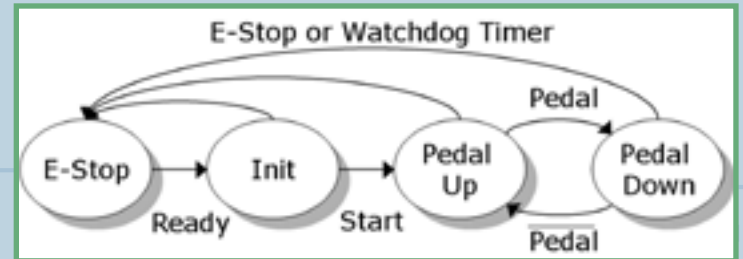


THE FULLY ASSEMBLED USB INTERFACE BOARD.

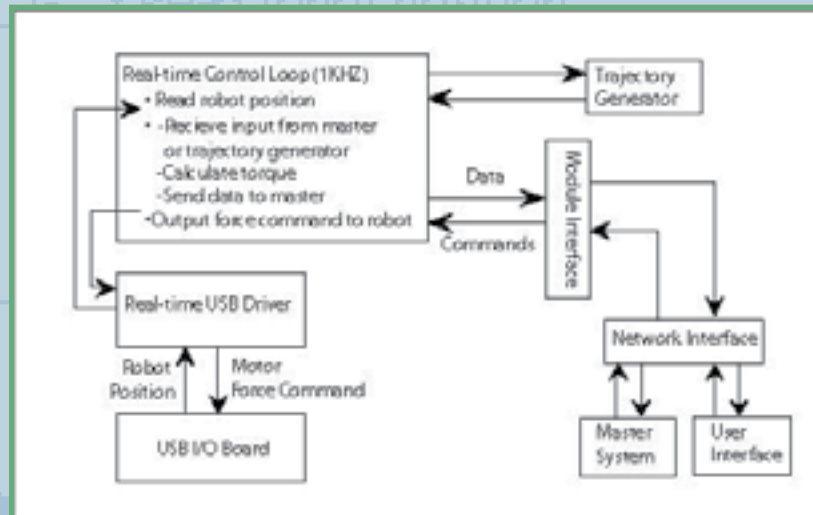
This surgical robot will have a variety of safety features. These features include a small number of operating states, brakes, an emergency stop (E-Stop) button, a watchdog timer, and a surgeon side foot pedal. The state of the system will be managed by a programmable logic controller (PLC). PLCs are a highly reliable off the shelf technology that can easily be programmed for small numbers of states. The control software will send requests to change states to the PLC and the PLC will in turn update the states. Additionally, a function in the Control Module produces a 10Hz square wave for a watchdog timer function in the PLC.



THE SYSTEM SOFTWARE IS MODULAR, AND ALLOCATION OF SOFTWARE MODULES TO COMPUTING HARDWARE IS FLEXIBLE EXCEPT FOR THE I/O BOARD SOFTWARE AND THE PLC LADDER LOGIC.



THE SYSTEM WAS DESIGNED TO CONSIST OF FEW STATES, AS SHOWN IN THIS FIGURE. MOVEMENT BETWEEN THESE STATES OCCURS DUE TO SIGNALS SENT INTO THE PLC. TRANSITIONS BETWEEN PEDAL UP AND PEDAL DOWN ARE CONTROLLED BY SURGEON FOOT PEDAL.



A BLOCK DIAGRAM SHOWING THE MAJOR CONTROL SYSTEM COMPONENTS. CONTROL SYSTEM RESIDES ON A LINUX HOST WITH REAL-TIME (RTAI) EXTENSIONS.

The design of this safety system is almost complete. The process of testing and constructing the various pieces of the system has begun, and the hope is to have the safety system constructed soon. The described software architecture is a crucial element in the overall surgical robot system. The expectation is that this system will provide a level of predictability, reliability and robustness sufficient for animal surgery evaluation.

Another aspect of this project is teleoperative control and mediating the destabilizing effects of time delay. A low-latency network protocol stack for RTAI decreases network latency, but cannot nullify the large and variable time-delays associated with operating across the Internet.

The researchers in the BRL are testing, applying and advancing the state of the art technology in this field. The system successfully performed a teleoperation demonstration across the UW campus from Kane Hall to the BioRobotics Lab with the first three DOF under control. This highly portable, network-enabled surgical platform has the potential to bring the skill of expert surgeons anywhere in the world.[EE](#)

FACULTY ADVISOR: PROFESSORS BLAKE HANNAFORD AND JACOB ROSEN  
 COLLABORATORS: PROFESSOR MIKA SINANAN - CENTER FOR VIDEO ENDOSCOPIC SURGERY (DEPT. OF SURGERY)  
 RESEARCH AREA: CONTROLS AND ROBOTICS, SURGICAL ROBOTICS, CONTROLS, TELEOPERATION  
 GRANT/FUNDING SOURCE: US ARMY - MEDICAL RESEARCH AND MATERIAL COMMAND GRANT NUMBER: DAMD-17-1-0202;\