Human Subjects Study, Ergonomic Controller and 3D Reconstruction for the Robo-ELF

Project Proposal for
Computer Integrated Surgery II

Group Member: Jong Heun Kim, Tae Soo Kim, Steve Park
Mentor: Kevin Olds

1. **Members:**

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    Tae Soo Kim
    Steve Park

2. **Mentor:**

    Kevin Olds

3. **Topic and Goal:**

    Human Subjects Study, Ergonomic Controller and 3D Reconstruction for the Robo-ELF: The goals of this projects are to create a system capable of providing quantitative endoscopic measurements and 3D reconstruction from several monocular endoscopic images, to design ergonomic controller for the robot, and to acquire clinical experiments results.

4. **Background / Statement of Relevance:**

    Traditional methods of laryngeal surgery involved disruption of the laryngeal framework which then led to motor and sensory deficits of the patients. Attempts to improve and possibly avoid such external invasive procedures led to advances in endoscopic laryngeal surgery that access the endolarynx through the mouth of the patient. Despite the enhancements to the endolaryngeal surgery triggered by improvements in microlaryngeal instrumentation and endoscopes, the current set up of endolaryngeal surgery continues to have disadvantages. The biggest shortcomings are the reduced depth perception from the monoscopic images, operator's distance from the surgical field and the crowded workspace for surgeons. [6]

    To address these problems with the non-robotic endolaryngeal surgical procedures, robotic endolaryngeal flexible (Robo-ELF) scope surgical robot has been proposed. The current state of the robot enables the surgeon to manipulate the robot using a joystick controller attached to the surgical bed while a real-time endoscope images are displayed on a monitor in the operating room. An unmodified flexible laryngoscope is attached to the robot and the surgeon is able to manipulate the scope with only one hand using the joystick.

    The Robo-ELF has undoubtedly improved the procedure of endolaryngeal surgery. However, there still exists shortcomings with the current design. Currently, in order to measure the level of subglottic stenosis, the otolaryngologist inserts increasing sizes of endotracheal tube into the stenotic segment to perform a leak test. Then the chosen endotracheal tube size is used to rank the severity of subglottic stenosis. Such an approach itself may alter the target that it is trying to measure and cylindrical endotracheal tubes are not completely apt for sizing stenotic segments.

    Another noticeable drawback of the Robo-ELF is its user-unfriendly joystick controller. Initially, commercially available 3D space mouse is used to control the Robo-ELF because the mouse intuitively mimics three degrees of freedom of the scope: rotation, up/down, and advance/retract. However, the disadvantage of the 3D space mouse is that it's very difficult to decouple user's movements to reliably separate degrees of freedom. To overcome this shortcoming, a controller with two digital joystick replaced the mouse interface. Because each digital joystick controls different degrees of freedom, the isolation of degrees of freedom is very reliable. Even though the joystick has good isolation, the controller lacks intuitive interface as the two joysticks does not move in the same direction as the scope and gradation as the digital joystick has only on or off states. To manipulate Robo-ELF well, a new design of controller with intuitive interface movements and analog gradation control with haptic feedback is required.

To improve the current subglottic stenosis procedures and endoscopic surgery in general, our software will enable 3D distance calculations from the 2D endoscope images and produce a 3D reconstruction of the airway. To enhance the usability of the Robo-ELF, we will develop a more ergonomic and intuitive joystick controller.

5. Technical Summary of Approach:

a. *Robo-ELF Human Subject Study*

Upon Institutional Review Board's approval, the clinical trial of the Robo-ELF will begin. The study procedures involve several tasks to compare the performance of traditional rigid scope and the flexible Robo-ELF.

With the patient's airway visualized with the laryngoscope, the Robo-ELF flexible scope will be passed through the shaft into the upper airway. The surgeon will manipulate the system using a 3-D joystick controller to evaluate the field of vision. Pictures and videos will be taken of the scene as well as the limits of the visual field. Then, the procedure advances to visualize areas that are traditionally challenging to approach. The surgeon will be manipulating the scope using one hand and the other hand to control a laryngoscopic suction. Further, the Robo-ELF will be fixed in a position to demonstrate the ability to perform two-handed procedures, such as above the vocal chord for a microlaryngeal surgery. Pictures and videos from the tasks will be evaluated by laryngologists to rate the quality of the images and as a novel method of endoscopic exam.

b. *Ergonomic Controller*

The new design of the joystick should have intuitive interface which mimics the scopes degrees of freedom, self-reorientation, and gradation control with haptic feedback for more precise velocity manipulation. For intuitive control of the Robo-ELF, the controller should have three active degrees of freedom which are advance/retract, rotate, and up/down. In addition, the controller implements gradation sensor such as potentiometer for more delicate manipulation of the speed of the scope.

For haptic feedback and reorientation of each degree of freedom in the controller, the Gimbal system is implemented.

The complete design assembly would be defined with Computer-Aided-Design software like autocad in detail. Most of the components in the controller design can be printed with 3D printer. Rest of the components such as motors, potentiometers, and metal bars in Gimbal system will be purchased. After acquiring and assembling all the parts of the design, we would test the functionality of the joystick with Arduino microcontroller and see if the controller produce desired gradation results according to the manipulation. Once the functionality of the joystick is verified with Arduino, the controller needs to be able to communicate with the Robo-ELF via Galil motor control. The controller with Galil motor system will be tested to manipulate the movement of the Robo-ELF. If the controller can move the Robo-Elf with all the desired functionalities, we can evaluate the defects of the controller meticulously and try to fix them.

c. *Measurements from monoscopic scope images / 3D reconstruction*

The vision component of the Robo-ELF project will yield a software that enables the user to measure 3D distance from 2D points on an endoscopic image. The software to produce such measurements require the following information: the focal length of the camera, the stereo baseline measurements and the disparity between stereo images. The block diagram below represents the means of obtaining relevant data and their relation to one another.

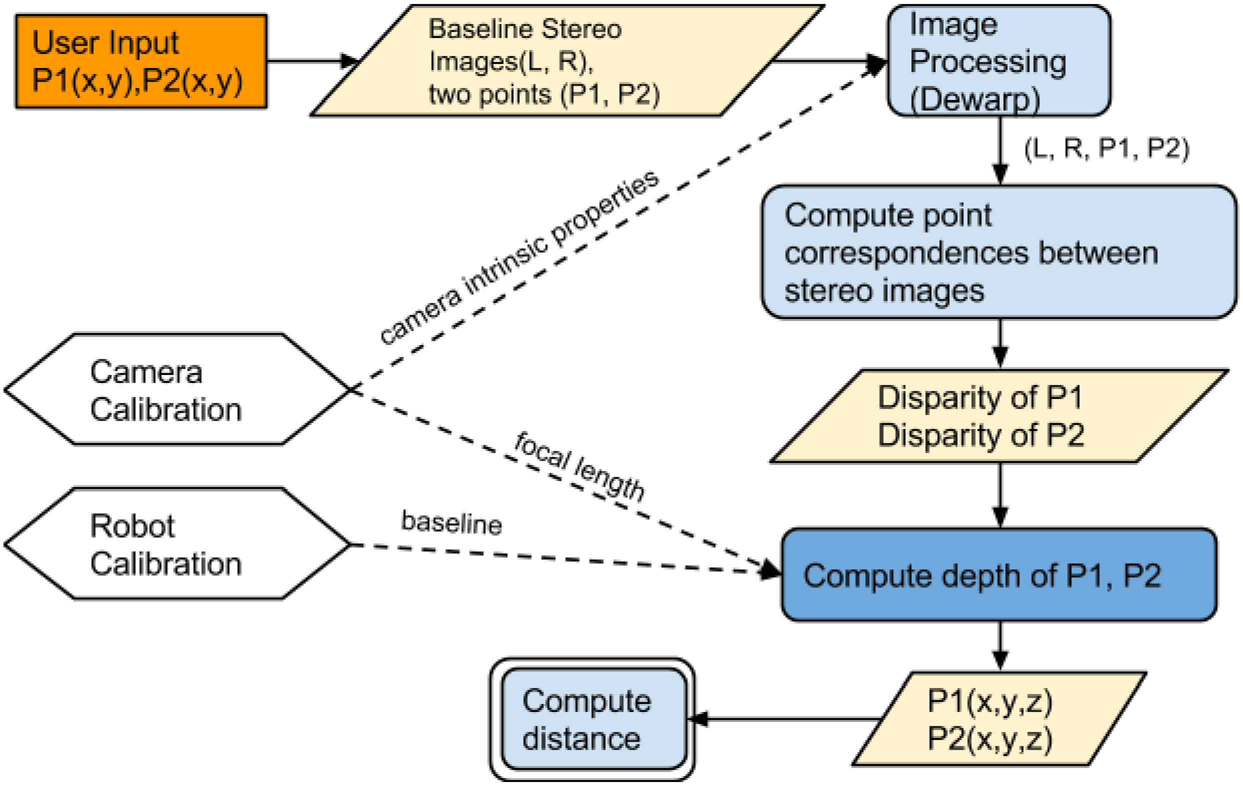


Figure 1. Flow diagram of stereo baseline 3D distance calculation from 2D image points.

The process specified above completes the minimum vision requirement of the project. Given a point P1 in one of the stereo images (assume the left image, L), the software must find the correct corresponding point P1' in the right image R. There are multiple suitable methods for identifying correspondences between stereo images. A leading idea is to use the SIFT (scale-invariant feature transform) feature descriptor for a specified window size around P1 in the first image and to find the corresponding point in the second image using the SIFT descriptor of P1. The correspondence solution will be found by picking a matching point P1' in the right image R that minimizes the cost function (in this case, the sum of squared differences between the SIFT descriptor values). Same procedure will be done for P2 as well.

With corresponding point pair (P1, P1'), the algorithm can calculate the disparity between the point pair. Disparity is the measure of the pixel distance between the corresponding points on the image. Having found all necessary parameters (focal length, *f*, baseline, *B,* disparity, *d*), the algorithm can not only find the depth, *Z*, of a given point P1 in the real world but also find its exact 3D coordinates. The calculation involves simple algebra that involves similar triangles as shown below.

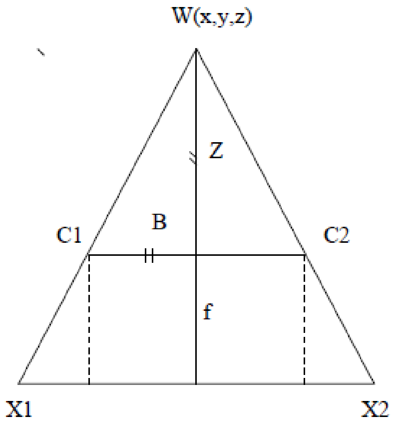


Figure 6.1: Stereo geometry.

Figure 2. Stereo baseline depth calculation problem set up.

Having solved for the real world coordinates of P1 and P2, simple distance calculation between the two points will yield a real 3D distance. The natural next steps of the project is to build on the stereo baseline 3D distance calculation algorithm and provide a 3D reconstruction algorithm from 2D images of the endoscope. Extend the problem of finding the depth of a single point to all points in the image. In other words, using the technique listed above, depth of all the points in the image will be calculated and as a result, the software can produce a 3D reconstructed model of the airway. Such an algorithm is intuitive and it benefits from the algorithm that we would have already developed for the distance calculation. However, possible shortcoming of the proposed 3D reconstruction technique is that it depends heavily on finding correct correspondences. A possible solution to the problem is to use the baseline information from the robot calibration and the symmetry of the stereo images. Knowing the baseline, the correspondence problem between the stereo images may only have to be solved once only. Such an approach to 3D reconstruction from 2D images still needs investigated further.

6. Deliverables:

1) Minimum (estimated March 26, 2014):
    - A. Assist Dr. Richmon in using the Robo-ELF Scope in the OR.
    - B. A fully designed ergonomic controller for the Robo-ELF Scope manipulation.
    - C. Documentation for the Robo-ELF Scope controller
    - D. Software to get real measurements from 2D scope images of an artificial setting.
2) Expected (estimated April 30, 2014):
    - A. Fully interfaced and functioning ergonomic controller with the Robo-ELF.
    - B. Software to get real measurements from 2D scope images of the larynx.
    - C. Software documentation
3) Maximum (estimated May 07, 2014)
    - A. Identify the disadvantages with the current prototype (feedback from surgeons) and produce an improved version of the controller.
    - B. Software that reconstructs a 3D model from the 2D scope images.

7. Dependencies

- a. Access to the Robo-ELF. ✓
- b. JHU IRB approval △
- c. Medical consult & OR visit △
- d. Images from the scope ✓
- e. Software for 3D reconstruction ✓
    - i. OpenCV, Matlab, CISST library ,C/C++
- f. Cost ✓
    - i. We will be provided if necessary up to $1,000 from the project funding.
    - ii. Majority of the parts of the ergonomic controller will be 3D printed and other mechanical parts will be either provided from the laboratory or can be purchased at a fairly low amount.
    - iii. The nature of the reconstruction project is on a virtual system; many of the tasks will not require spending money.

8. Management Plan:

a. Regular weekly meeting with Kevin

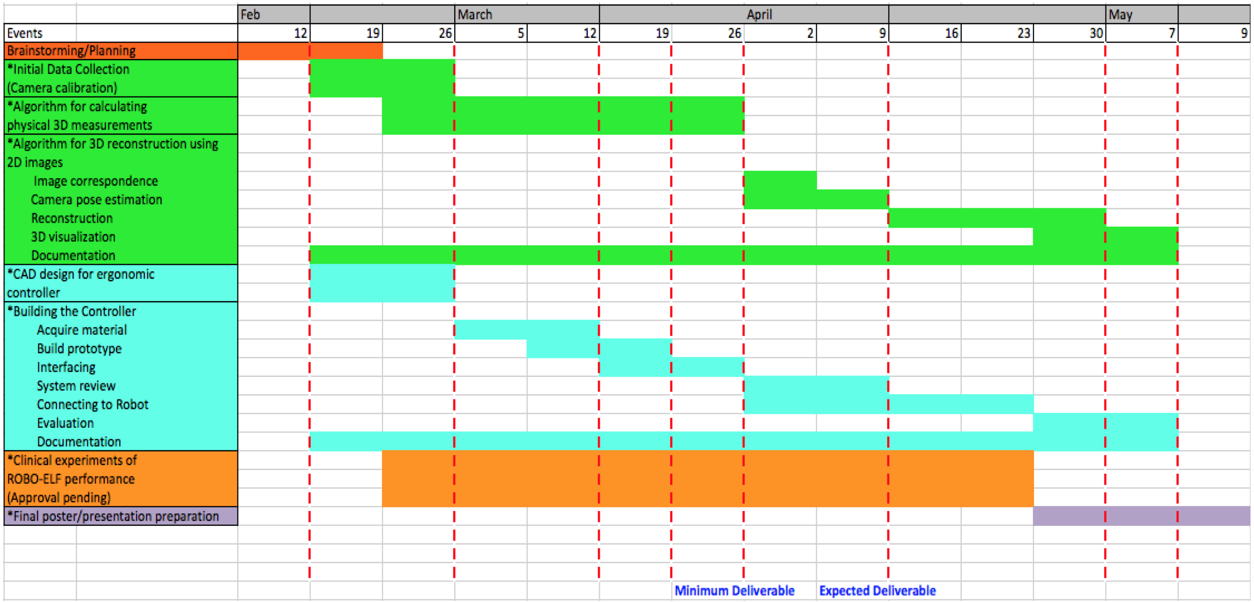
b. Biweekly meetings amongst team members

c. Task leaders:

- ☐ Jong Heun Kim: Clinical
- ☐ Tae Soo Kim: 3D reconstruction
- ☐ Steve Park: Controller

9. Timeline

Enlarged version of the timeline is appended.

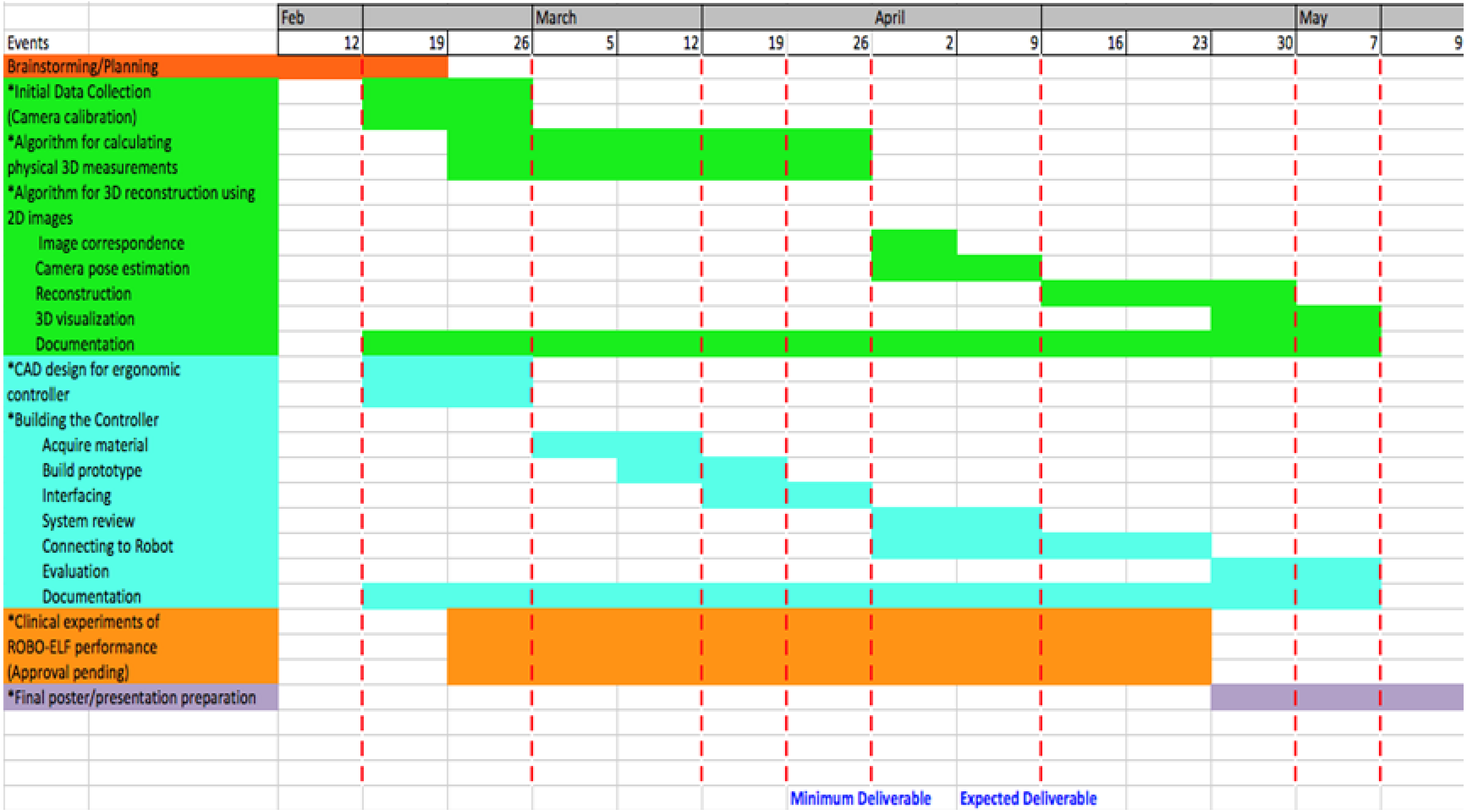


10. Milestones

Milestone	Planned Date	Expected Date	Status
Scope image data collection	Feb. 12	Feb. 12	**Completed**
Camera calibration	Feb. 26	Feb. 12	**Completed**
Robot calibration	Feb. 26	Feb. 20	In progress
Initial CAD design of the controller	Feb. 26	Feb. 24	In progress
Order and acquire all controller parts	Mar. 12	Mar. 12	
Build prototype	Mar. 19	Mar. 19	
Interfacing with the robot	Mar. 26	Mar. 24	
3D distance from 2D scope images of an artificial scene	Mar. 26	Mar. 12	
Minimum deliverable met			
3D distance from 2D scope images of the larynx	Apr. 09	Apr. 09	
Expected deliverable met			
Get input from Dr.Richmon about the controller	Apr. 09	Apr. 09	
3D reconstruction of an artificial scene using the scope images	Apr. 30	Apr. 30	
3D reconstruction of the larynx	May. 07	May. 07	

11. Reading List

1) Darius Burschka, Ming Li, Russell Taylor, and Gregory D. Hager. Scale-Invariant Registration of Monocular Stereo Images to 3D Surface Models. In *Proceedings of IROS*, pages 2581-2586, 2004.
2) Darius Burschka and Gregory D. Hager. V-GPS – Image-Based Control for 3D Guidance Systems. In *Proc. of IROS, pages 1789*–1795, October 2003.
3) Darius Burschka and Gregory D. Hager. V-GPS(SLAM): – Vision-Based Inertial System for Mobile Robots. In *Proc. of ICRA, April* 2004.
4) Olof Enqvist, Fredrik Kahl, Carl Olsson. 2011. Non-Sequential Structure from Motion. *Computer Vision Workshops (ICCV Workshops), 2011 IEEE International Conference*. p. 264-271.
5) Daniel Mirota, Russell H. Taylor, Masaru Ishii, and Gregory D. Hager. Direct endoscopic video registration for sinus surgery. In *Medical Imaging 2009: Visualization, Image-guided Procedures and Modeling. Proceedings of the SPIE*, volume 7261, pages 72612K-1 - 72612K-8, February 2009.
6) Kevin Olds, Alexander T. Hillel, Elizabeth Cha, Martin Curry, Lee M. Akst, Russell H. Taylor, Jeremy D. Richmon. Robotic Endolaryngeal Flexible (Robo-ELF) Scope: A Preclinical Feasibility Study. *The Laryngoscope*; 2011; 121; 2371- 2374
7) Toan D. Pham, Rucker Ashmore, Lisa Rotelli. 2011. Proportional joystick with integral switch. U.S. Patent 7931101, filed October 13, 2006, and issued April 26, 2011.
8) Hanzi Wang, Daniel Mirota, and Gregory D. Hager. A generalized kernel consensus based robust estimator. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 32(1):178-184, 2010.
9) William M. Wells III, Paul Viola, Hideki Atsumi, Shin Nakajima, Ron Kikinis. 1996. Multi-modal volume registration by maximization of mutual information. *Medical Image Analysis*. v. 1. p 35–51.



	Feb			March		April						May	
Events	12	19	26	5	12	19	26	2	9	16	23	30	7	9
Brainstorming/Planning	🟧	🟧												
*Initial Data Collection (Camera calibration)		🟩	🟩											
*Algorithm for calculating physical 3D measurements			🟩	🟩	🟩	🟩	🟩							
*Algorithm for 3D reconstruction using 2D images														
Image correspondence								🟩						
Camera pose estimation								🟩	🟩					
Reconstruction										🟩	🟩	🟩		
3D visualization												🟩	🟩	
Documentation		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
*CAD design for ergonomic controller		🟦	🟦											
*Building the Controller														
Acquire material				🟦	🟦									
Build prototype					🟦	🟦								
Interfacing						🟦	🟦							
System review								🟦	🟦					
Connecting to Robot								🟦	🟦	🟦	🟦			
Evaluation												🟦	🟦	
Documentation		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
*Clinical experiments of ROBO-ELF performance (Approval pending)			🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
*Final poster/presentation preparation												🟪	🟪	🟪

Minimum Deliverable Expected Deliverable