Ultrasound-based Visual Servoing

Group 8 Final Project Report

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Abstract

Ultrasound is well-suited for intraoperative imaging because it is cheap, portable, provides images in real-time, and does not use ionizing radiation. However hand-held ultrasound is user-dependent because it requires dexterity to obtain high-quality images, and certain features such as bone or air cannot be penetrated. In contrast, preoperative imaging provides much greater anatomical detail and considerable clinical utility, but it produces static images that differ from current reality due to organ movement and deformation. This project implements a robotic ultrasound system that uses visual servoing to automatically guide an ultrasound probe to a volume of interest within a preoperative image. The system allows the doctor to obtain accurate anatomy in real time by integrating a preoperative image with the current ultrasound scan of the patient, which combines the advantages of preoperative and intraoperative imaging.

1. Introduction

Certain medical procedures require a high level of anatomical precision, such as cancer tumor removal or neurosurgery. Although preoperative imaging modalities such as CT and MRI allow for a high level of contrast and spatial resolution, this data differs from the current anatomy of the patient during surgery due to factors such as breathing. As a result, intraoperative imaging is necessary to obtain the real-time anatomy of a patient's organs.

Ultrasound is commonly used for intraoperative imaging due to providing high temporal resolution without an acquisition or processing delay so that images can reveal the current anatomy. These units are portable enough to be transported to a patient's bedside, are substantially lower in cost compared to other methods of imaging, and do not produce ionizing radiation unlike x-ray. Consequently, ultrasound is easy to access in medical facilities.

The main drawbacks of ultrasound are that certain organs which are easy to visualize in preoperative imaging are difficult to image with ultrasound. For example, ultrasound cannot penetrate air which makes imaging of the lungs difficult, and bony structures cause attenuation of ultrasound. Organs may also appear substantially different with ultrasound relative to preoperative imaging modalities due to the physics of sound wave reflection, so a computer-assisted method may be needed for registration with a prior image. Hand-held ultrasound requires a skilled operator to manipulate the device, so its usage requires an ultrasound technician to assist the surgeon or a surgeon who is trained to acquire ultrasound images.

Due to the greater precision and dexterity of a robot for positioning of an ultrasound probe, robotic ultrasound has the potential to improve patient outcomes and shorten procedure times. Robotic ultrasound also presents ergonometric benefits to technicians because they must hold the transducer in awkward positions for prolonged periods of time, sometimes exerting large forces, and suffer from an unusually high incidence of musculoskeletal disorders.[1] The ability of a robot to track the locations of two-dimensional images allows a computer to reconstruct a three-dimensional ultrasound volume, which overcomes the limitations of spatial perception in traditional ultrasound.[2] Robotic ultrasound provides the opportunity for real-time feature tracking and registration with other modalities during surgery.

This project focuses on ultrasound-based visual servoing, which is the automatic feedback control of an ultrasound probe based on its current image and a desired image. With visual servo control, a transformation is computed between the current image and the desired image and the robot moves according to the transformation. Visual servo control is repeated until the difference between the ultrasound probe image and the desired image is sufficiently small. Ultrasound-based visual servoing has been shown to exhibit stable convergence with a tracking error that converges to zero when a nontrivial number of feature points are tracked in a two-dimensional ultrasound image. [3]

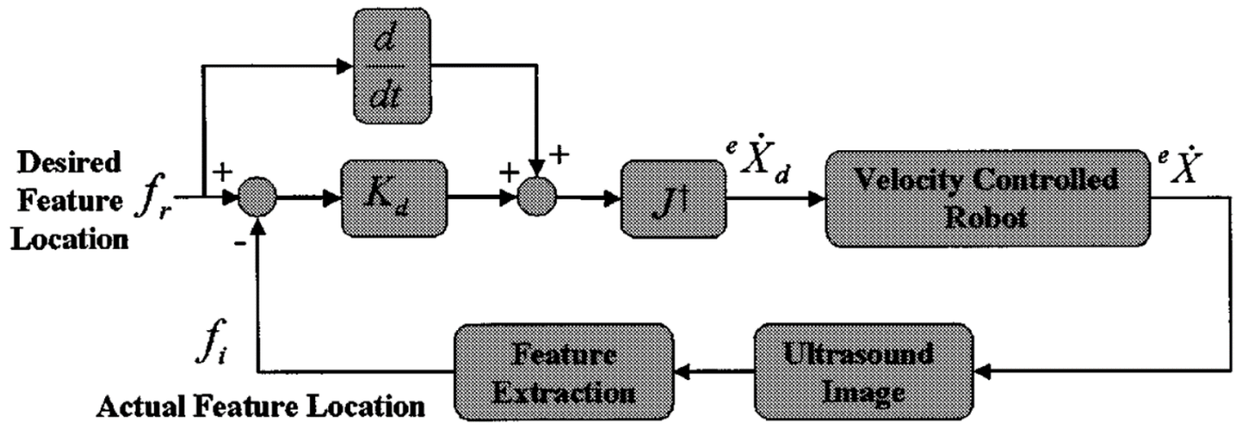


Figure 1: Ultrasound visual servo controller [3]

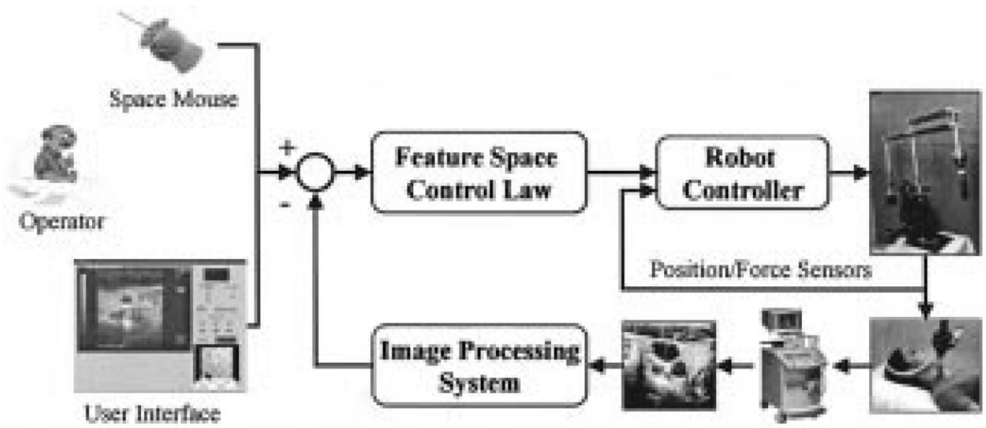


Figure 2: Block diagram of visual servoing system used by Abolmaesumi et al. (2002)

Prior work has focused on the use of an ultrasound probe controlled by a human operator via a telemanipulation system, or automated tracking of a feature in the ultrasound probe image, which has mainly involved moving an ultrasound probe to a desired feature based off a prior ultrasound image. For example, Abolmaesumi et al. (2002)[3] described a visual servoing system that automatically positions an ultrasound probe above the carotid artery in real-time and allows shared control with a human operator. Vitrani et al. (2005)[4] describe the automatic guidance of a surgical instrument to a tracked target location using three-dimensional ultrasound.

In contrast, visual servoing in this project is used for the automatic guidance of an ultrasound probe to select a volume of interest from a preoperative image, such as CT, MRI, or preoperative ultrasound. Once the volume is selected, the robot would acquire the current ultrasound scan at that location. This approach makes it feasible to integrate a preoperative image with an intraoperative ultrasound image so that a doctor can obtain updated anatomy during surgery, even when deformations and organ movement cause the preoperative image to differ from reality.

2. Project goal

The goal of this project is to develop and implement an ultrasound-based visual servoing system for intraoperative robotic ultrasound using ImFusion, a medical computer vision library containing algorithms for three-dimensional compounding of ultrasound scans and image registration. The system would use a preoperative image to serve as the reference image of the patient's anatomy, and the doctor would select a volume of interest from the reference image to have an ultrasound probe scan the patient in real-time at that location. Since image registration algorithms have already been implemented, this project focuses on establishing communication between ImFusion and a KUKA iiwa lightweight robot to form an automatic feedback control loop.

3. Methodology

Existing ultrasound-based visual servoing systems have consisted of a slave manipulator that carries the ultrasound probe, a computer which performs visual servo control, and a user interface which allows the operator to select a feature of interest. Similarly, the system setup for this project consists of a KUKA robot with an ultrasound probe attached to its tooltip and a workstation containing software that obtains the current ultrasound probe image and location of the robot, lets the operator select a volume within the reference image, then moves the robot according to the transformation from the current probe image to the volume of interest to implement visual servo control.

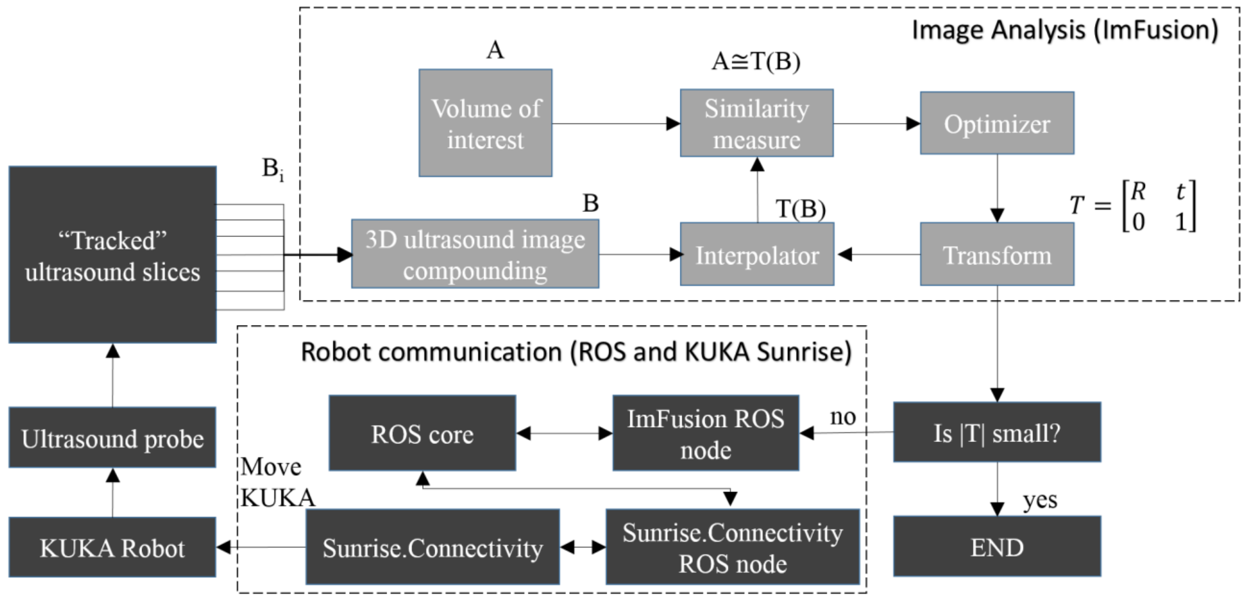


Figure 3: Block diagram of the visual servoing system for this project, showing software modules of this project in dotted boxes. Light gray corresponds to image analysis, and dark gray corresponds to robot communication.

The project consists of two main software components: i.) an image analysis module which calculates the transformation between the ultrasound probe image and volume of interest, and ii.) a robot communication module which exchanges information between ImFusion and the KUKA robot regarding the current robot state. The image analysis module is also responsible for using ultrasound slices with known position and orientation to obtain a three-dimensional volume. While much of the image analysis capability had been already included in ImFusion, communication between ImFusion and the KUKA robot has not been implemented at the time.

Image Analysis

ImFusion provides existing C++ modules for ultrasound volume compounding from two-dimensional slices with known position and orientation, three-dimensional ultrasound-MRI and ultrasound-ultrasound registration, as well as functions that obtain the transformation between images. The software also provides a SDK that allows the addition of new plugins using QT Creator for the development of graphical user interfaces.

The ImFusion SDK is used to create a new plugin that communicates with the KUKA robot controller. The plugin takes as input the 2D B-mode images from the ultrasound probe along with the current location of the probe in robot coordinates. It stores a 3D reference image, the volume of interest, and a 3D ultrasound volume at the probe's current location obtained from aligning the 2D B-mode images based on position. Built-in modules are used to obtain the three-dimensional rotation and translation between the ultrasound volume at the probe's current location and the reference image. The plugin subsequently communicates instructions to move the ultrasound probe according to the computed transformation.

Robot communication

To establish communication between ImFusion and the KUKA robot, a possible alternative was to use the Robot Operating System (ROS) framework to create nodes that send and receive pose messages. Some benefits of ROS are that it provides a peer-to-peer topology for interprocess communication, is multilingual, abstracts robot functionality from middleware, and provides several hundred open source packages.[5] This approach would also involve using Sunrise.Connectivity, an interface for communication with the KUKA robot, for intermediate message passing between ImFusion and KUKA. Since ImFusion only runs on Windows, a possible pitfall was that the core ROS system might have compatibility issues with Windows because it is only designed for Unix-based platforms.

Another approach was to run the core ROS system using MATLAB and use a ROS node for Sunrise.Connectivity, then use an existing OpenIGTLink plugin to communicate between ImFusion and ROS. This would maintain ability to use ROS functions, and ImFusion already contains a module for OpenIGTLink.

A third approach was to create an OpenIGTLink interface for Sunrise.Connectivity that enables communication with the OpenIGTLink interface for ImFusion. This approach would have avoided Windows compatibility issues, but a disadvantage would have been that ROS provides greater existing functionality than OpenIGTLink.

A possible idea that was not considered was directly interfacing between ImFusion and KUKA Sunrise since this would have introduced tight coupling between software components.

The approach for this project was to use "win_ros", a ROS library that supports native Windows application development, to avoid compatibility issues. This allowed creation of a ROS node for ImFusion and usage of a ROS server for passing messages with an existing ROS node in Sunrise.Connectivty. In addition, all other CAMP projects now have the ability to use ROS with ImFusion to enable greater reuse of existing robot functionality.

5. Results

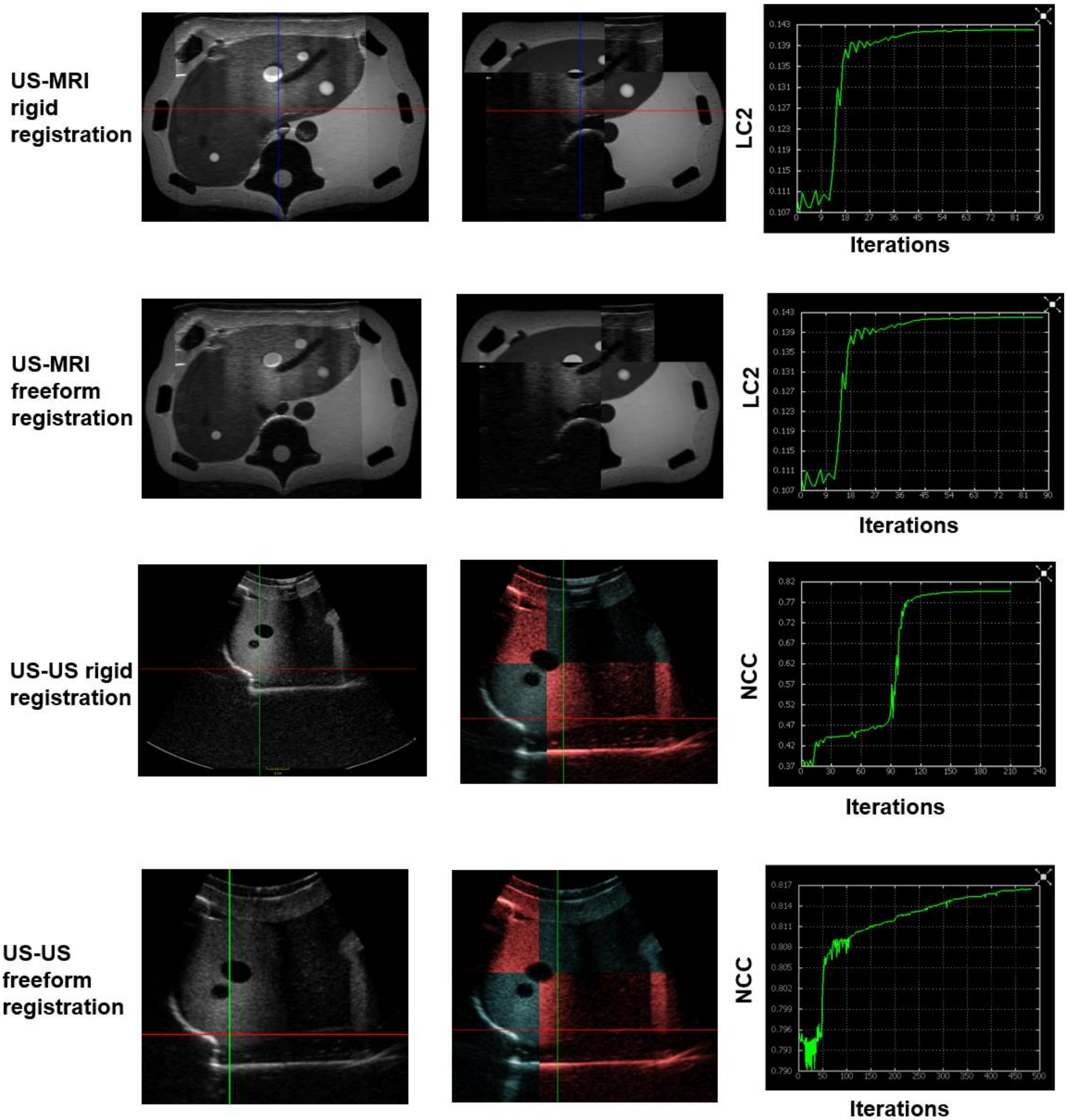


Figure 4: Experimental results of visual servoing with US-MRI and US-US registration, with both freeform and rigid registration. The photos depict the registration of the ultrasound image and the volume of interest once the robot has moved to its final position. The left photo shows both photos combined, and the right photo shows the current ultrasound volume in the lower left/upper right and the volume of interest in the upper left/lower right. Visual servoing accuracy is quantified using the linear correlation of linear combination (LC2) metric [6] for US-MRI and normalized cross correlation (NCC) metric for US-US.

Figure 5: KUKA Robot with ultrasound phantom and workstation running ImFusion during the visual servoing experiment

Visual servoing was performed on the ultrasound phantom shown in Figure 5. The experiment was conducted using ultrasound-MRI and ultrasound-ultrasound registration given an initial ultrasound position, and both rigid registration and freeform registration were used. The visual servoing algorithm was applied until the transformation between the current ultrasound image and the volume of interest were sufficiently small. Next, accuracy of final registration between the ultrasound probe image and the reference image was measured as a function of iterations.

In all cases, the robot accurately obtains the ultrasound scan corresponding to the volume in the preoperative image, as observed from the results of registration of the ultrasound volume with the volume of interest from the reference image. These images are shown in Figure 3. The ultrasound-ultrasound registration gives an image with less misalignment relative to the ultrasound-MRI image.

Accuracy was quantitatively defined using normalized cross-correlation (NCC) for ultrasound-ultrasound registration and linear correlation of linear combination (LC2) [6] for ultrasound-MRI. These metrics measure the similarity between two images, with the intuition that the images will become more similar as their alignment becomes more optimal. It was observed that registration accuracy converges to a stable value after a large number of iterations.

Both rigid and freeform give comparable accuracy, which may be due to the ultrasound phantom having a stiff design that prevents the occurrence of deformities.

6. Conclusions

The results provide a proof-of-concept that ultrasound-based visual servoing is feasible for obtaining the updated anatomy of a patient during surgery. Although prior work has focused on visual servoing using registration between two ultrasound images, the results present evidence that visual servoing between ultrasound and MRI might be feasible.

Since testing was only done using a single ultrasound phantom, future work should involve testing with additional phantoms to see if results are reproducible. Additional testing also needs to be done with more preoperative images.

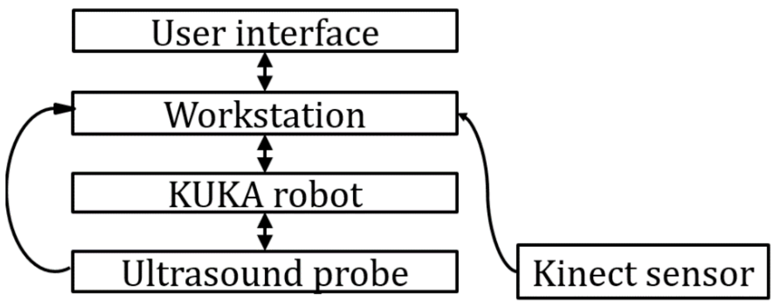


Figure 6: Future system setup of the visual servoing system with a Kinect sensor

Future work will involve integrating the existing ImFusion plugin with a Kinect sensor. This would provide visual feedback of the patient when the ultrasound probe is in a location away from the body of the patient. This is necessary because no ultrasound feedback is available when the probe is separated from the patient by air. Another future task is to integrate this project with a current project that also uses visual servoing with ImFusion, but communicates with the KUKA robot using OpenIGTLink. Both of these would require similar image registration functionality and should be used to create a general-purpose module for visual servoing.

7. Project Management

The original deliverables for the project are as follows:

- Minimum
    - ImFusion plugin for automated ultrasound-MRI and ultrasound-ultrasound registration that returns transformation between the three-dimensional images
    - ImFusion plugin for communication between ImFusion and KUKA robot
- Expected

- Given an initial ultrasound probe image and volume of interest, find the transformation between the two and move robot to location of volume of interest
  - Perform validation of path planning on different ultrasound phantoms
  - Evaluate performance of different registration techniques
  - Provide documentation of completed portions
- Maximum
  - Given only the volume of interest, obtain the corresponding ultrasound image and move robot to final location regardless of initial position using Kinect sensor

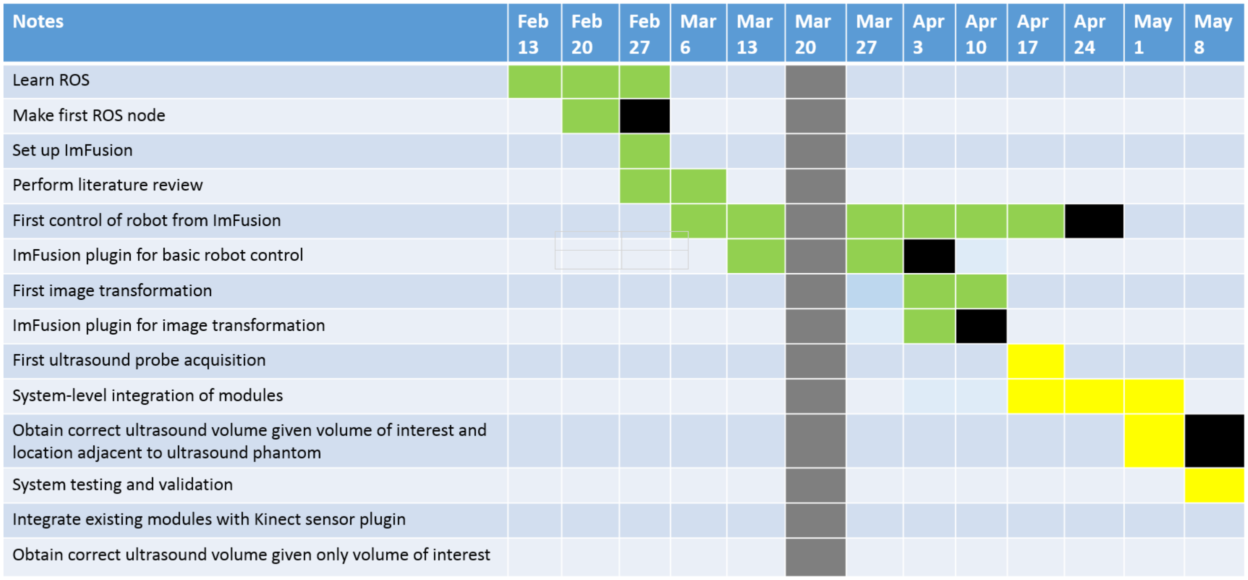
I was able to accomplish all of the minimum deliverables but not the maximum deliverable. For the expected deliverables, I was not able to perform validation of path planning on different ultrasound phantoms because there was only one ultrasound phantom that I had access to. I was able to test ultrasound-ultrasound and ultrasound-MRI registration but did not have the data or time to perform ultrasound-CT registration. My expected deliverable of having the robot move the ultrasound probe to the volume of interest given an initial position took three weeks longer than expected, which resulted in limited time for experimental validation.

My original timeline was as follows:

Notes	Feb 13	Feb 20	Feb 27	Mar 6	Mar 13	Mar 20	Mar 27	Apr 3	Apr 10	Apr 17	Apr 24	May 1	May 8
Learn ROS													
Make first ROS node													
Set up ImFusion													
Perform literature review													
First control of robot from ImFusion													
ImFusion plugin for robot control													
First image transformation													
ImFusion plugin for image transformation													
First ultrasound image acquisition													
System-level integration of modules													
Obtain correct ultrasound volume given volume of interest and location adjacent to ultrasound phantom													
System testing and validation													
Integrate existing modules with Kinect sensor plugin													
Obtain correct ultrasound volume given only volume of interest													

Black – milestones **Green – min deliverables** **Yellow – expected deliverables** **Red – max deliverables**

My revised timeline is as follows:



Black – milestones **Green – min deliverables** **Yellow – expected deliverables** **Red – max deliverables**

A major issue was that controlling the robot from ImFusion took much longer than expected, which resulted in the delay of other tasks. This task required integrating my ImFusion plugin with a KUKA Sunrise module for controlling the KUKA robot, which I was depending on other students to assist with. Despite these issues, I was able to work on integrating the image transformation and robot control plugins within ImFusion by simulating robot movements and ultrasound images to validate that the visual servo control would behave as expected.

All of my original dependencies were resolved on time and are listed below:

Dependency	Reason	Resolution
Ability to meet with mentors	To discuss current progress and get advice	Schedule weekly meetings with Bernhard Fuerst on Wednesdays at 9am
Permission to use ImFusion	ImFusion is proprietary software which is not freely available to the general public	Research agreement with CAMP allows free usage of software for academic purposes and already have permission from Prof. Navab

J-Card access to the Robotorium and Mock OR	To gain access to the KUKA robot and a workstation for ImFusion	Get Hackerman Hall JCard access form signed by a faculty member then give to Alison Morrow
Computer with GPU powerful enough to run ImFusion	ImFusion uses GPGPU computing for fast image processing and needs the ability to operate in real time	Work with mentors to obtain an account on workstation in Robotorium which has a Tesla GPU
Ultrasound probe and phantoms	To validate the path planning of the KUKA robot	Should already be located in Mock OR
Kinect sensor	The maximum deliverable requires being able to start with the ultrasound probe away from the patient. This requires a sensor which can find the patient's location.	Should already be located in Mock OR

8. Lessons Learned

This project allowed me to understand the design of a visual servo control system. It also allowed me to understand how ROS and KUKA Sunrise work. Another lesson learned is to have a backup plan in case one of the expected milestones get unexpectedly delayed.

9. References

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