Master's Thesis

Disturbance Observer Design for Robot-Assisted Eye Surgery

Author: Stephanie Shamiyeh

Supervisor: Prof. Luigi del Re
Prof. Maarten Steinbuch (TU/e)
Prof. René van de Molengraft (TU/e)

Partner: TU Eindhoven, Netherlands
PRECEYES GmbH

Finished: January 2015

Abstract

This master thesis was developed within a cooperation between the Eindhoven University of Technology (TU/e) and her spin-off company PRECEYES. Together they developed the surgical system for vitreo-retinal surgery this thesis is based on.
Problems in vitreo-retinal surgery are the need for high precision and steady movements within an unergonomic position for the surgeon. The PRECEYES Surgical System solves these problems as operating with it, the surgeon can adjust his position to his individual measurements and needs and the tremor gets filtered out. Additionally it is possible to scale the movements which leads to a higher precision.
In this work a disturbance observer is designed which detects possible external disturbances as fast as necessary to prevent damage to the patient. After estimating the disturbance, its severity is rated and an appropriate action to prevent damage will be executed.
The developed system detects disturbances based on the error signal on which it sets a variable threshold. A band designed disturbance observer estimates direction and amplitude of the external force as cause of the disturbance. Distinguishing is based on the available signals: the reference, the measured position and the estimated force. The developed method is based on the dynamics of the model and evolved with an empirical approach. It detects every disturbance as soon as the external force is high enough to overcome the non-backdriveability of the system and leads to a measurable change in position against reference.
Note: It was not the goal to change the system to solve the task optimally but to solve the task as well as possible with the given system.

Introduction

First, a definition for disturbances is provided. Since the error is defined as the deviation of the position from the reference, it is very reliable and with less noise than other available signals. Therefore I define a disturbance as the cause of a maximum allowed error:
A disturbance is defined as external input that causes an absolute error (between reference and position) bigger than 2.5 mrad.
The measurement of joint position is given in radians, this is why the limit is also given in radians. This is only a maximum and with smaller velocities and different actions of the surgeon with the motion controller the limit can be set lower.
The unexpected events during a procedure can be categorised in two groups:

- Obstruction (passive):
  - The IM bumping into an object (e.g. the microscope)
  - The IM twists or clamps draping or tubing
- Collision (active):
  - An object (e.g. hand, elbow) bumping into the IM
  - Twisted tubes release sudden energy into the system

While obstructions are defined as passive disturbances, which means no energy is given into the system, collisions are active since something is actively bumping into the system hence inserting energy.
Based on these definitions the **problem statement** is as follows:

Development of a system that detects obstructions and collisions while operating the PRECEYES Surgical System.

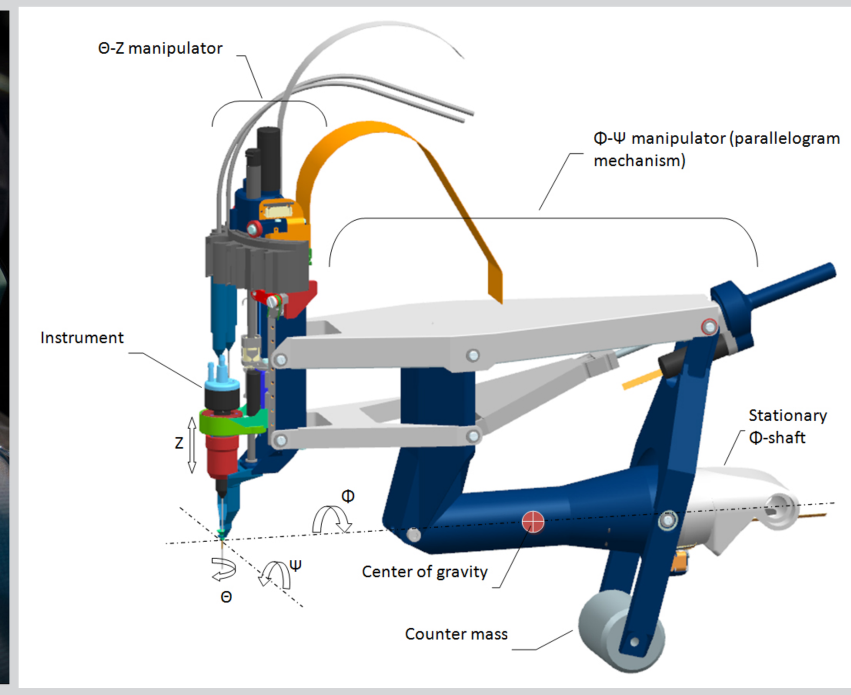
As this is a very wide assignment, this work is concentrated on the main two degrees of freedom (DoFs) Φ and Ψ of the system.

Implementation

First step to solve this task was to set up a model of the given prototype. This was only partly successful as the friction dynamics were not properly researched. Due to time issues we decided to go for a working solution without a working model. So the next step was to take all valuable information out of the model and improve it further with a heuristic approach. A band designed disturbance observer (bdDOB) was configured to filter the measurable parameters. It was tuned with physical knowledge of the model on one hand and with data from experiments on the other hand. All the given information from joint position measurement, derived velocity, the error signal and the output of the bdDOB was taken into account to set dynamic bounds for the error. Out of these bounds, a disturbance is detected. Then it is detected whether the disturbance is accelerating or decelerating the instrument within the patient's eye.

Pictures

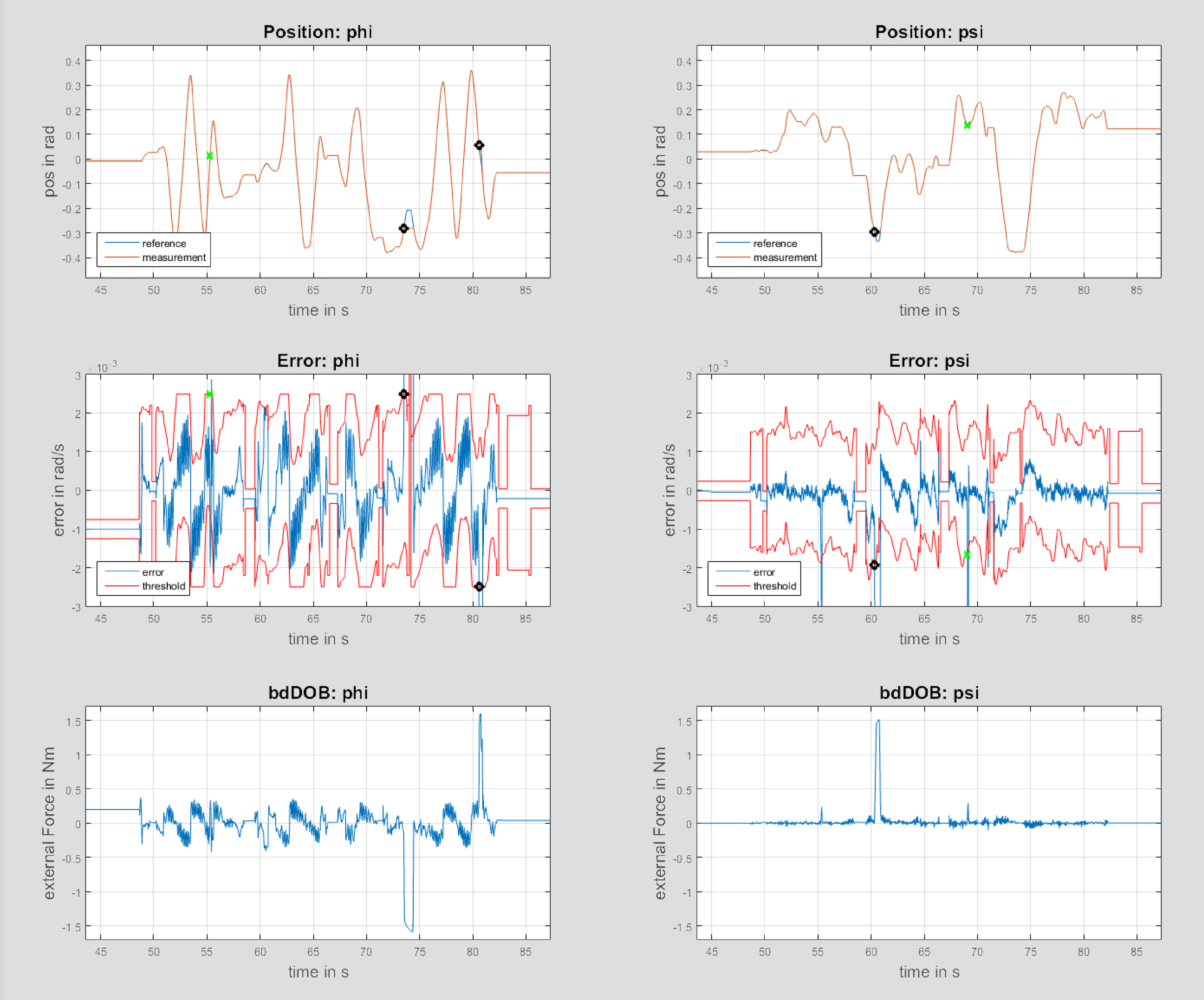
Preceyes System During Surgery



Scheme of the Surgical System

Experimental Validation

To validate the work several experiments have been performed on the working prototype. Collisions and Obstructions have been tested in all possible directions and with different intensities. The following figure shows one of those tested trajectories with the detected disturbances marked. In green there are collisions to be seen while the black dots mark obstructions.
First row of pictures shows the position in both directions, second row shows the error and the set bounds and third row shows the signal of the band designed disturbance observer (bdDOB).



For detecting disturbances there has been a nearly 100%-rate of success. Only disturbances too small to do any harm have not been detected, which is not necessary after all.

The task to distinguish between obstructions and collisions has been changed to distinguish between accelerating and decelerating collisions, due to impossibility of catching obstructions and collisions defined as before with the given sensors.

Conclusion and Outlook

The highest premiss to prevent any harm from the patient and his eye has clearly been successfully fulfilled. Additionally the requested accuracy has been undercut.

Outcome of the experimental validation with a high number of tested situations shows a surprisingly good result, although the algorithm is partly based on heuristics and not only on physical equations.

For the team from PRECEYES there are a few recommendations to improve the system further. Main point to go on with that work is to improve the model of the system with deeper research of the friction model. Based on that a fully working simulation can be built up and an algorithm based on physics without heuristic tuning is possible to be developed.

Of course additional sensors would also be a way to further improve accuracy and give more information to the surgeon in case of an emergency and therefore help him react better.