Appendix

Error behaviour in repeatability validation

For each achieved configuration in the repeatability validation experiment, the pose data is averaged over a period of 4 seconds. The resulting data for the displacement in Z-direction upon reaching configuration C_4 is presented in Fig. 19a). The corresponding distribution of measurements is shown in Fig. 19b). It can be seen that the readings follow a normal distribution around a mean of 5.36mm with a standard deviation of 0.03mm. A χ^2 goodness-of-fit is performed to determine the suitability of describing the individual read-ings for a given pose as a normal distribution. Across all configurations, the mean p value associated with the fit is 0.34 ±0.28. It is therefore concluded that this hypothesis holds across the workspace and thus, the time-averaged pose is a suitable indicator for the true pose of the SEE.

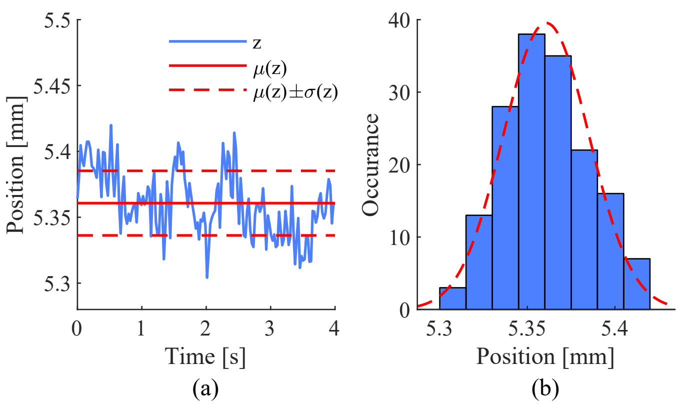

Fig. 19: Sampling of EM tracker data for defined pose over 4sec (a) and corresponding distribution of measurements (b).

Safety considerations

The use of a soft robotic system can help to greatly reduce the contact contact forces upon undesired patient or motions of the robot itself.

The build-up of contact force with a clamping contact between robot and the patient constrained by the patient bed can lead to discomfort and potentially injury [57]. To determine an approximate occurring force for a patient motion of 1cm against a rigid robot, we can calculate the following. The Young's modulus for visceral contents can be approximated by E_{vis} = 8.42kPa [58]. Assuming a circular contact of 10mm radius (r) with a tissue thickness (d) of 10mm, the stiffness of the visceral contents can be determined as

$$K_{vis} = E\pi r^2/d = 39.37\text{N/mm}$$

If the patient moves against a stationary rigid robot over the distance Δx = 10mm, the contact force experienced by patient and robot is

$$f_{rigid} = K_{vis} \cdot \Delta x = 39.37\text{N/mm} \cdot 10\text{mm} = 393.7\text{N}$$

For the soft robot, the system stiffness is combined in form of two serially-connected springs. In case of the lowest transversal stiffness of the soft robot (K_{SEE} = 1.51N/mm), one can compute for the combined stiffness

$$K_{comb} = (1/K_{vis} + 1/K_{SEE})^{-1} = 1.45\text{N/mm}$$

The resulting force build-up upon contact is then only 21.69N. Considering the reduction in contact force when exposed to an involuntary patient or clinician motion, it can be assumed that the use of soft robots instead of rigid ones could greatly reduce contact forces when a patient is exposed to a clamping contact.