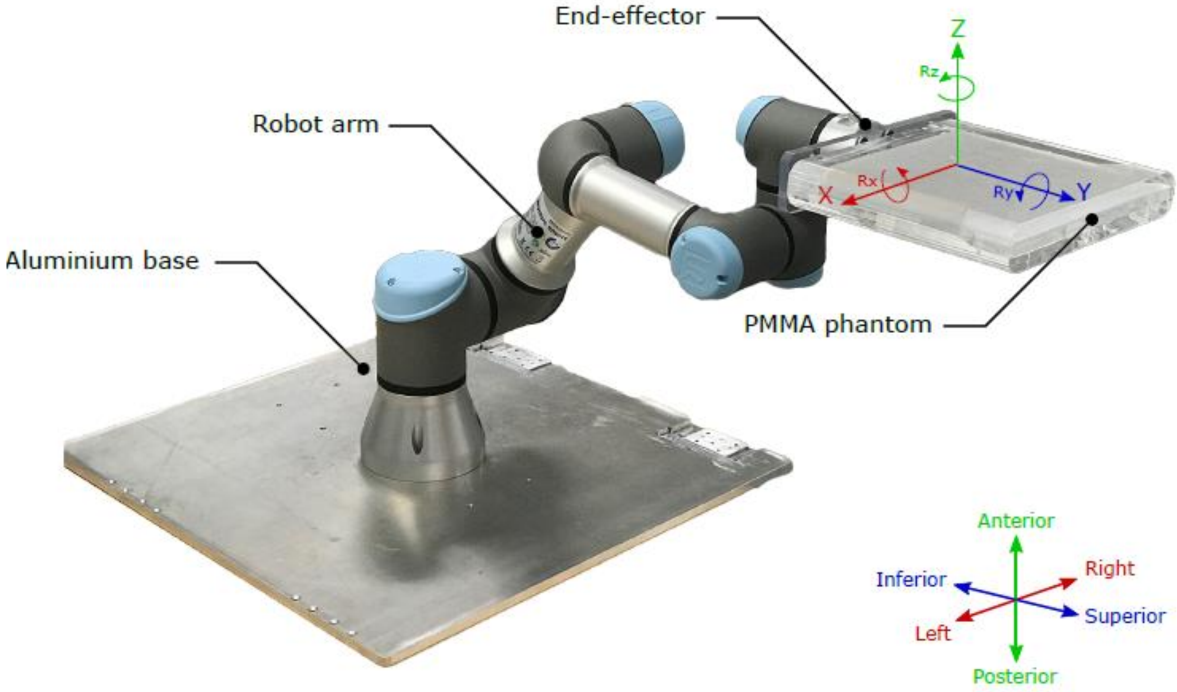
Justification

Four prostate, two liver, and three lung motion traces were selected for validation. From over 200 traces, these traces were chosen to represent the spectrum of motion exhibited by tumours during treatment delivery. A slow-moving stable trace was selected which represents the dominant observed motion of the prostate. Three other uncharacteristic prostate motion traces were selected which include erratic, continuous drift, and large high-frequency motion. For liver, large translational and rotational motion was selected caused by the breathing motion of the diaphragm. The selected lung traces included large translational AP motion, large rotational motion along the SI axis, and large translational motion along SI axis. The prostate and liver traces were recorded using KIM and the lung traces were recorded using Calypso motion tracking system.

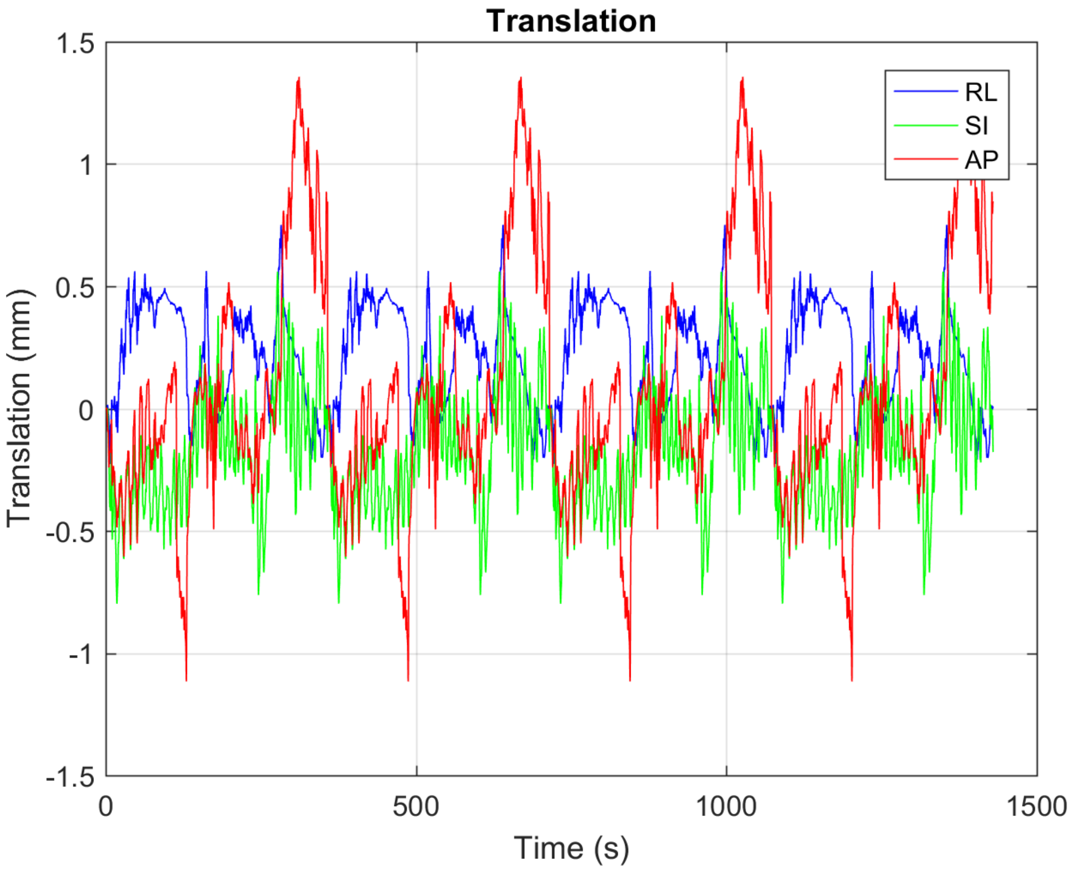
Several pre-processing steps were applied to the motion traces. Firstly, all motion traces were resampled to 5Hz. The prostate traces were pre-processed to reverse any gated couch shifts during treatment due to the large motion of the target. The baseline of the liver and lung traces were shifted to oscillate around the origin by subtracting the mean motion in each axis, sampled from the first 20 seconds. This simulated a setup in which the patient was centred in the internal target volume (ITV). Since the original motion traces were recorded between 1 to 10 minutes, multiple repetitions of these trace were stitched together to generate a 20 min sequence. Finally, the selected traces were filtered to remove measurement noise produced by the KIM and Calypso systems and ensure smooth motion of the robotic phantom, which is more representative of real physiological tumour motion. Filtering was performed by measuring the static motion from each system and calculating the periodogram, an estimate of the spectral density of the measurement data. A custom low-pass filter was then determined based on the cut-off frequencies outside the measurement (signal) frequency, thereby retaining relevant motion frequencies related to breathing and heartbeat.

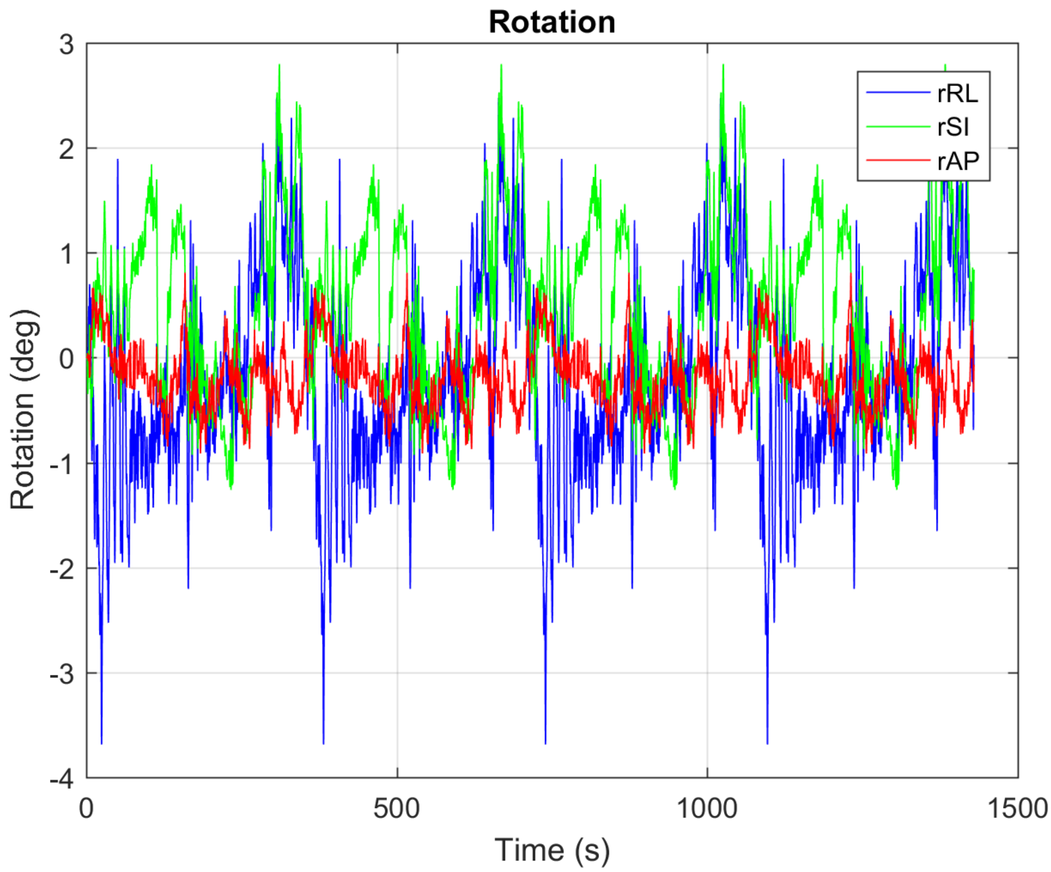
Coordinate system

Figure 1 shows the coordinate systems used by the robotic arm. The coordinate system defined by x (left-right), y (superior-inferior) and z (anterior-posterior) represents the origin of motion (rotation and translation). All the input data is transformed relative to the robots coordinate system before the motion is executed. The coordinate system of the motion is based on the International Electrotechnical Commission (IEC) 61217 clinical protocol for radiotherapy equipment which is represented by the right-handed coordinate system. In this standard positive x, y and z are pointed left, superior, and anterior respectively, with positive rotation pointing anticlockwise in x, y and z, when the reference frame is looking from the left-right (LR), superior-inferior (SI), and anterior-posterior (AP) directions respectively. Zero degrees of rotation in the x, y and z-direction are along the y, x, and y-axis respectively.

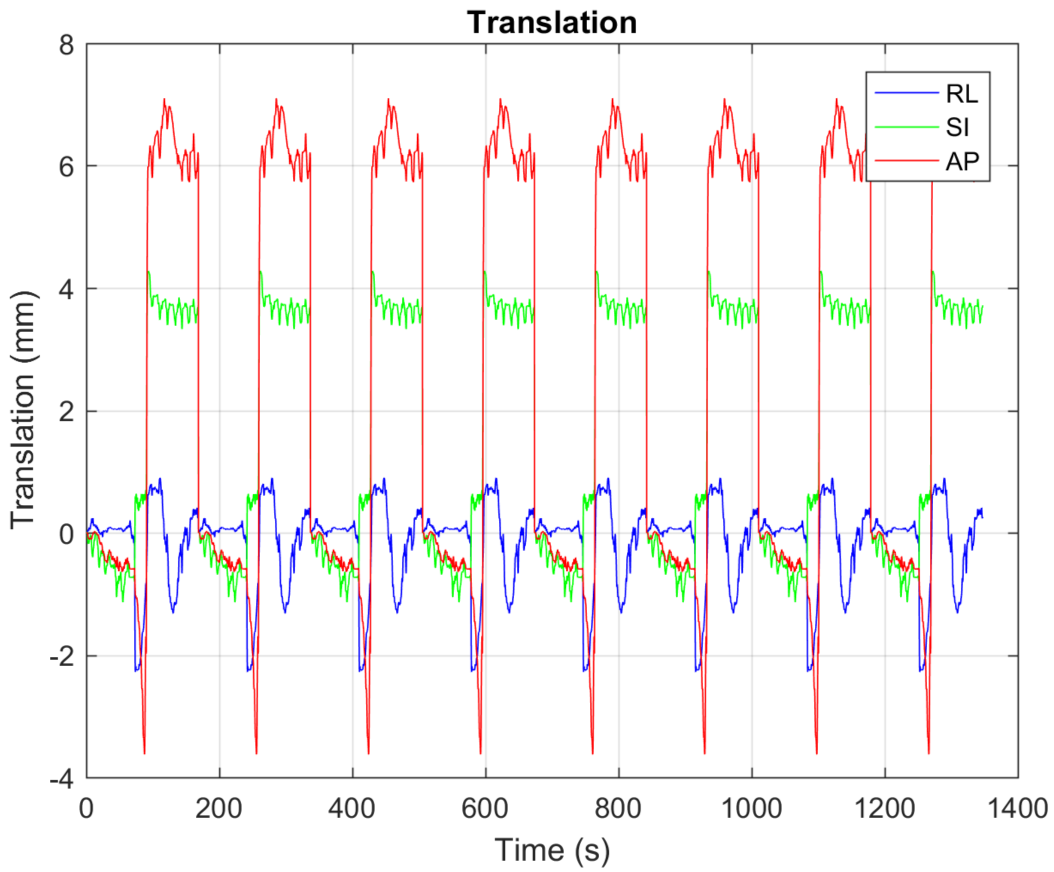

End-effector
Robot arm
Aluminium base
PMMA phantom
Z
Rz
X
Rx
Ry
Y
Anterior
Inferior
Right
Superior
Left
Posterior

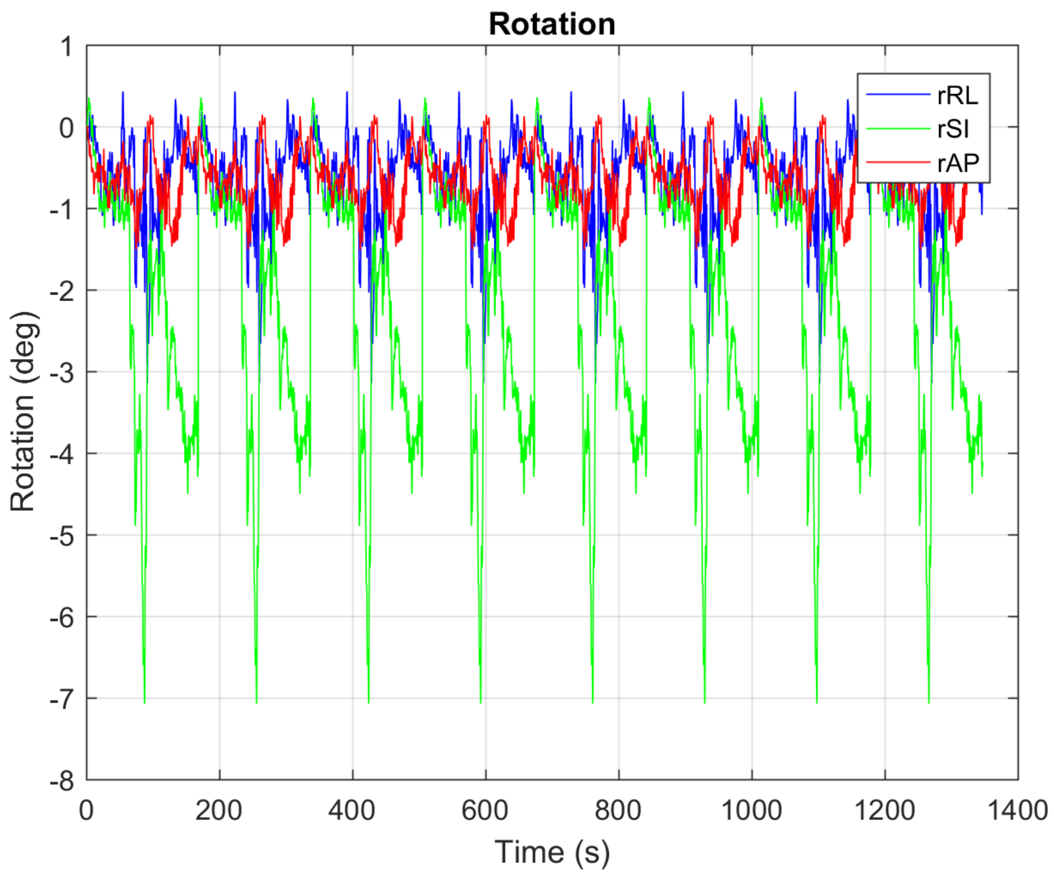
Prostate: Trace 1 (Stable target at baseline both rot and trans)



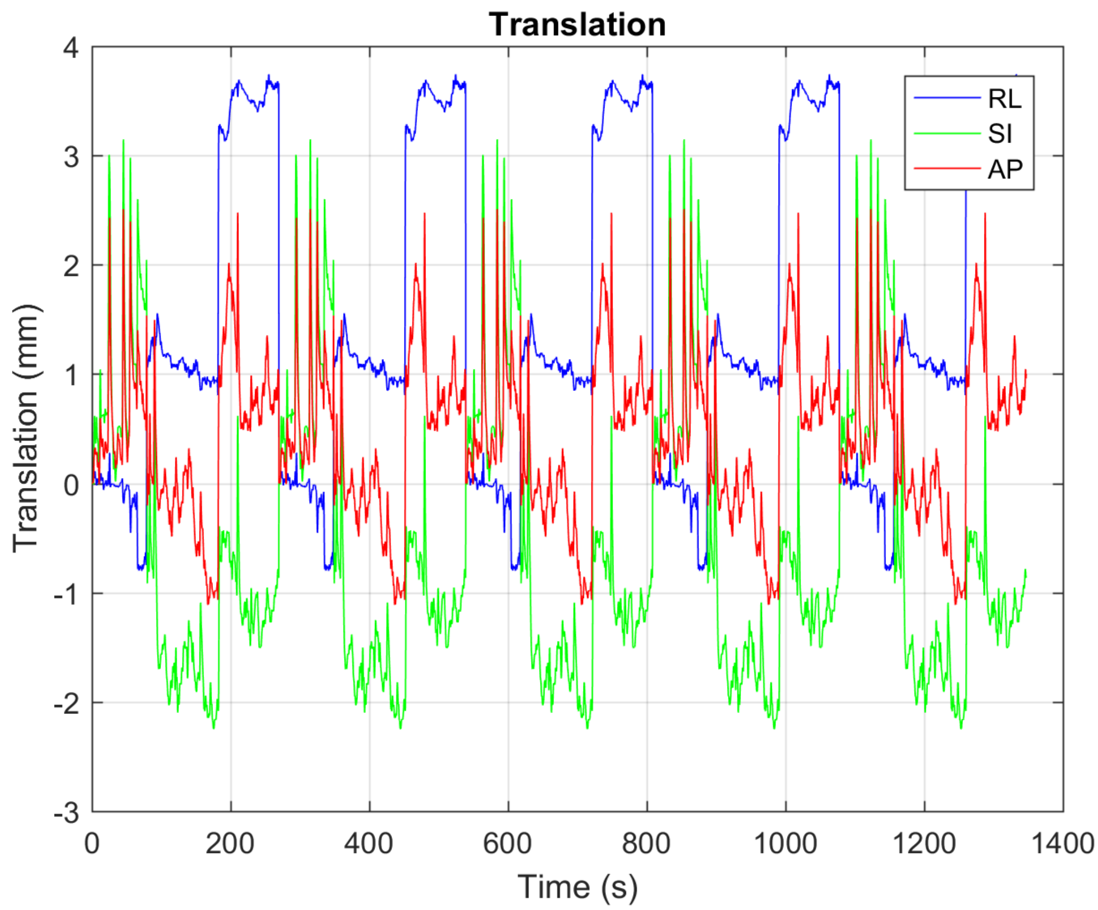


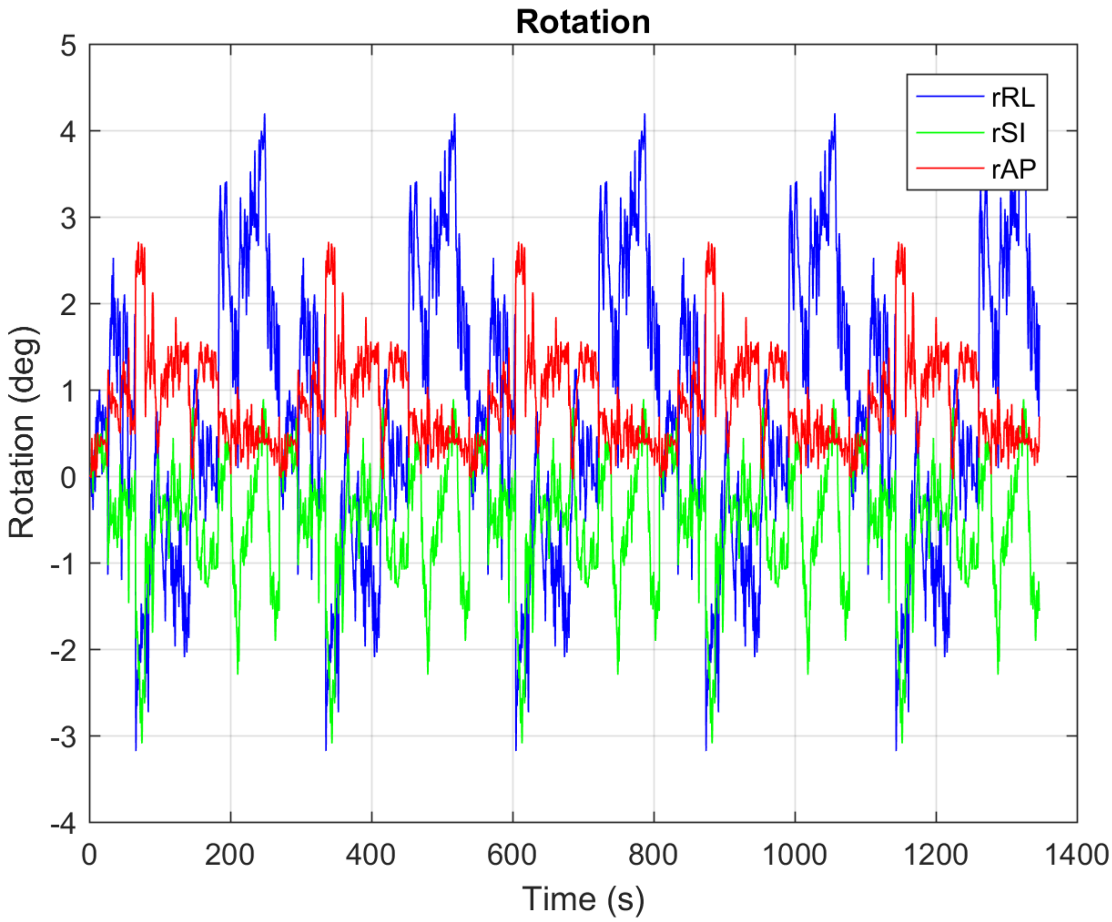
<u>Prostate:</u> Trace 2 (Persistent excursion)



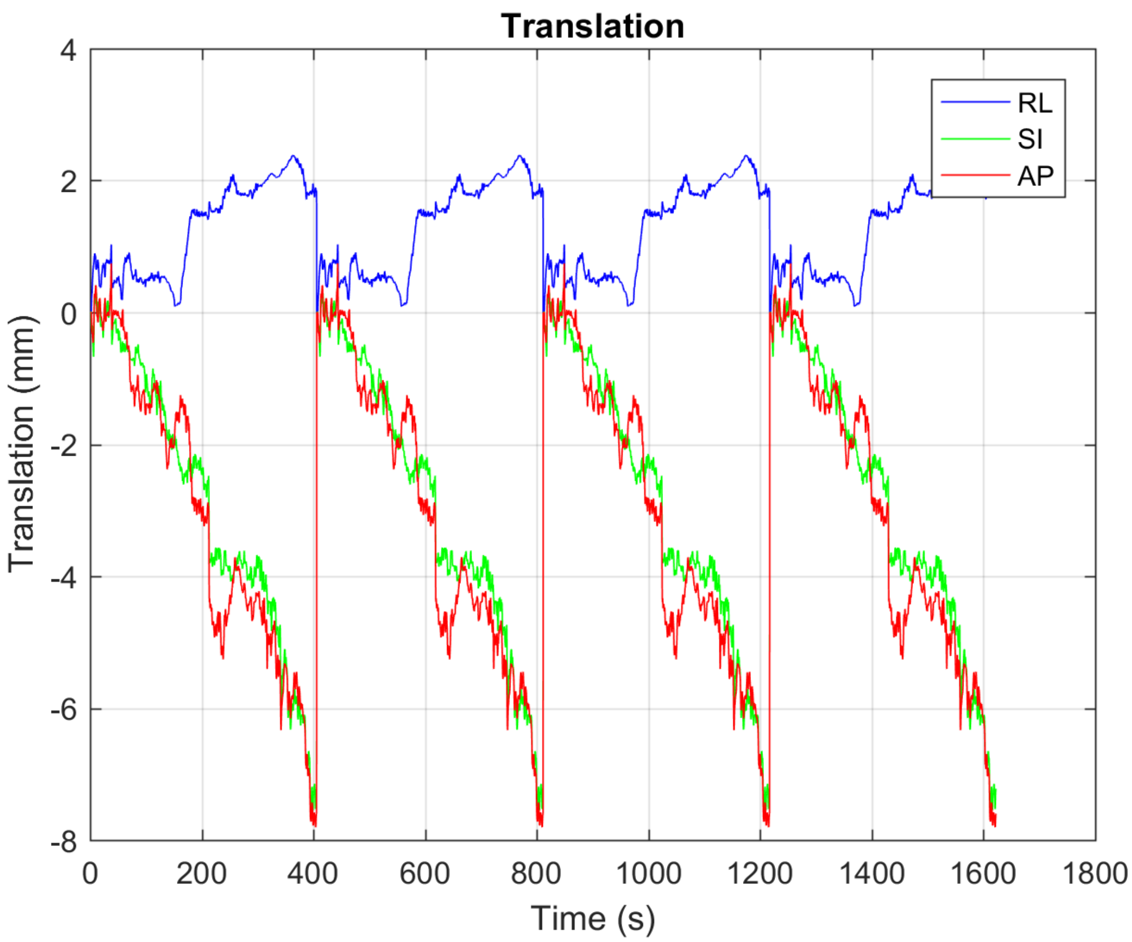


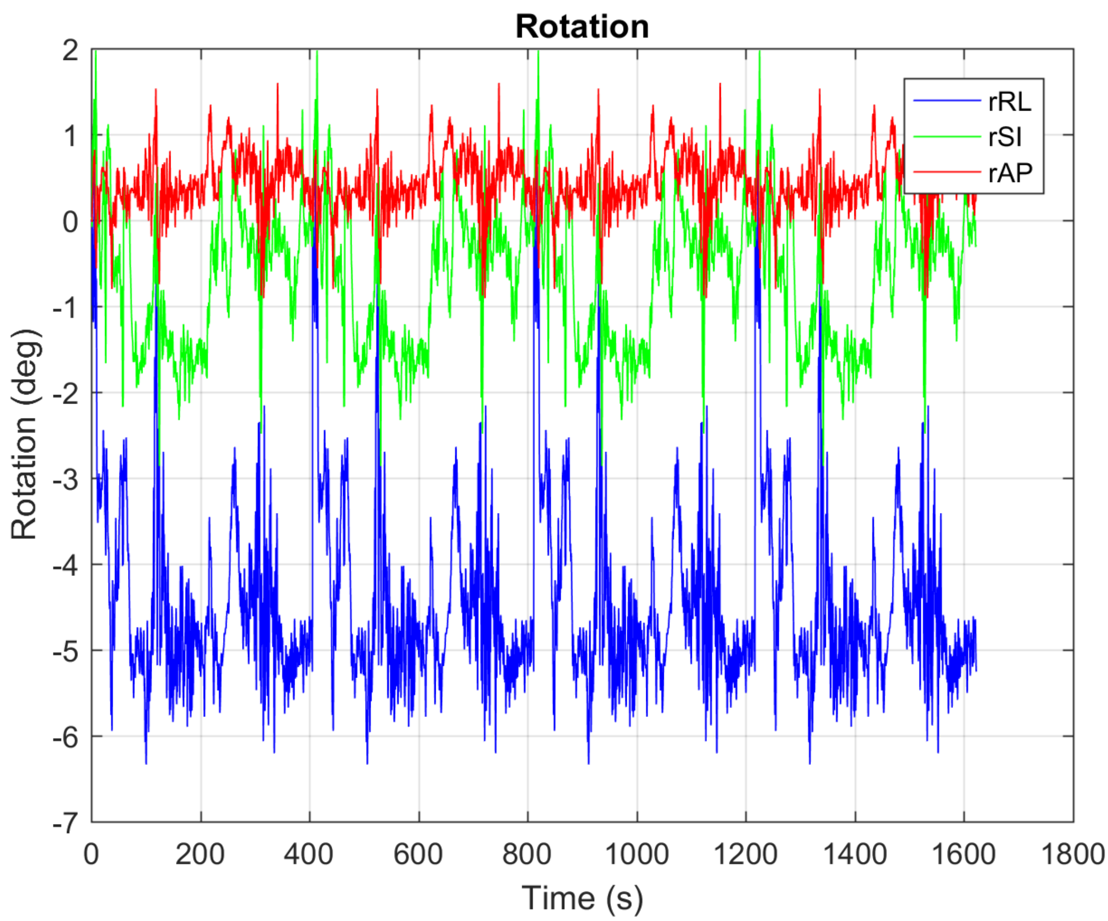
<u>Prostate:</u> Trace 3 (Erratic behaviour)



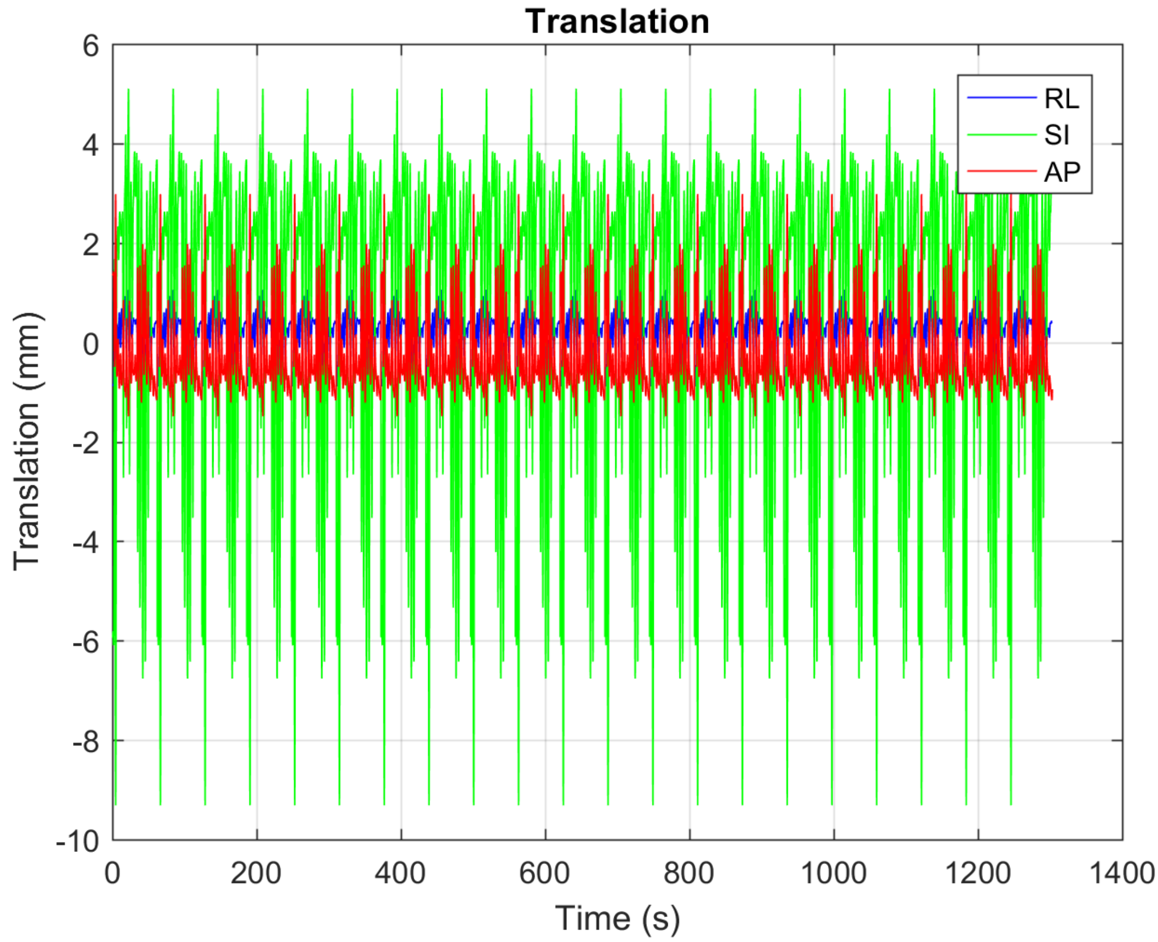


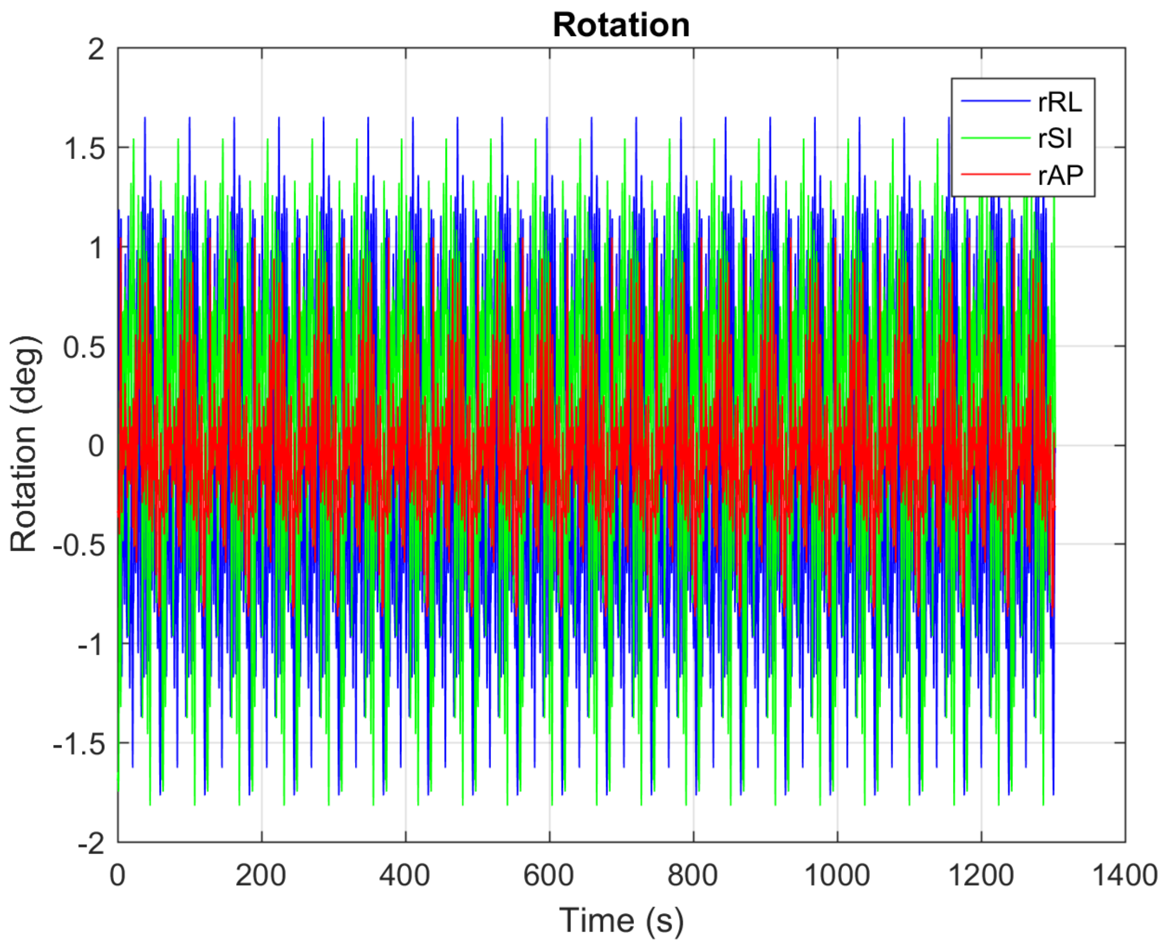
<u>Prostate:</u> Trace 4 (Continuous target drift)



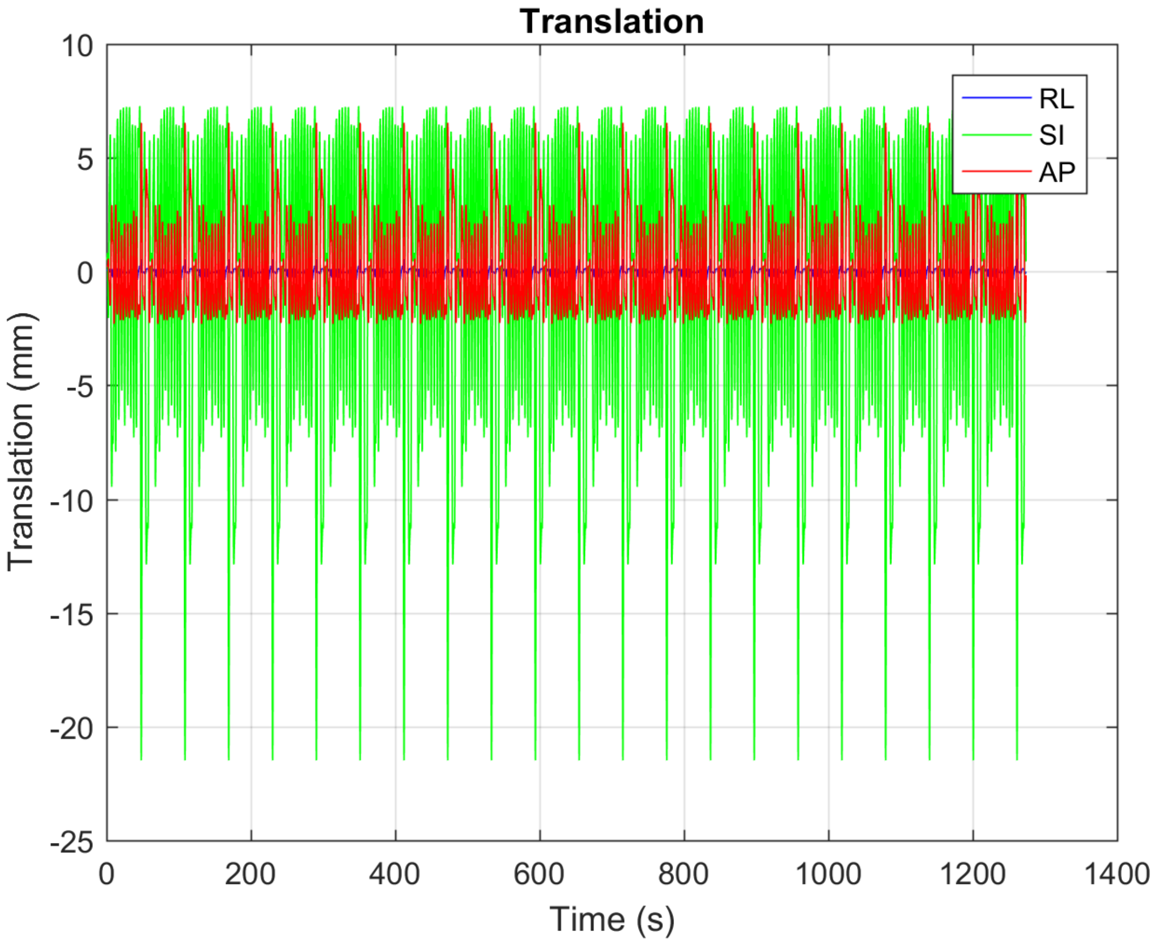


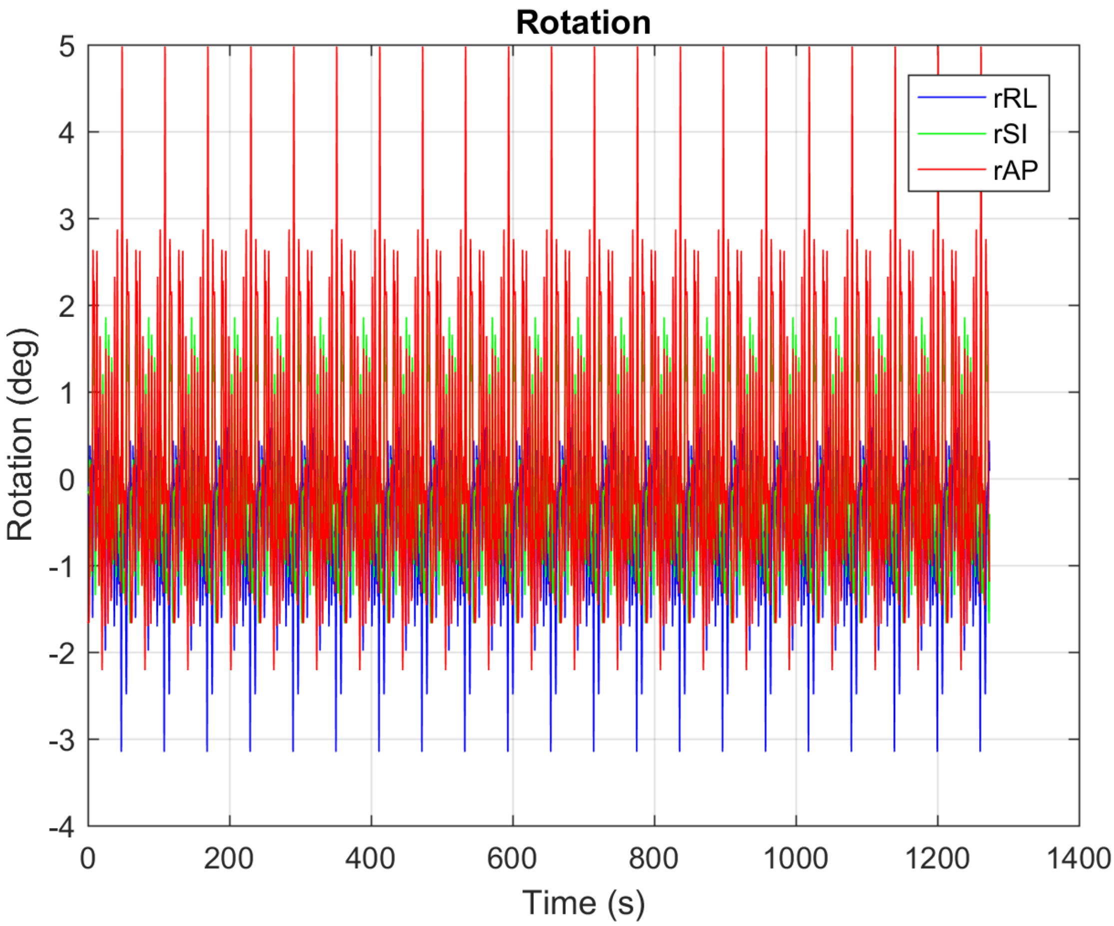
<u>Liver:</u> Trace 1



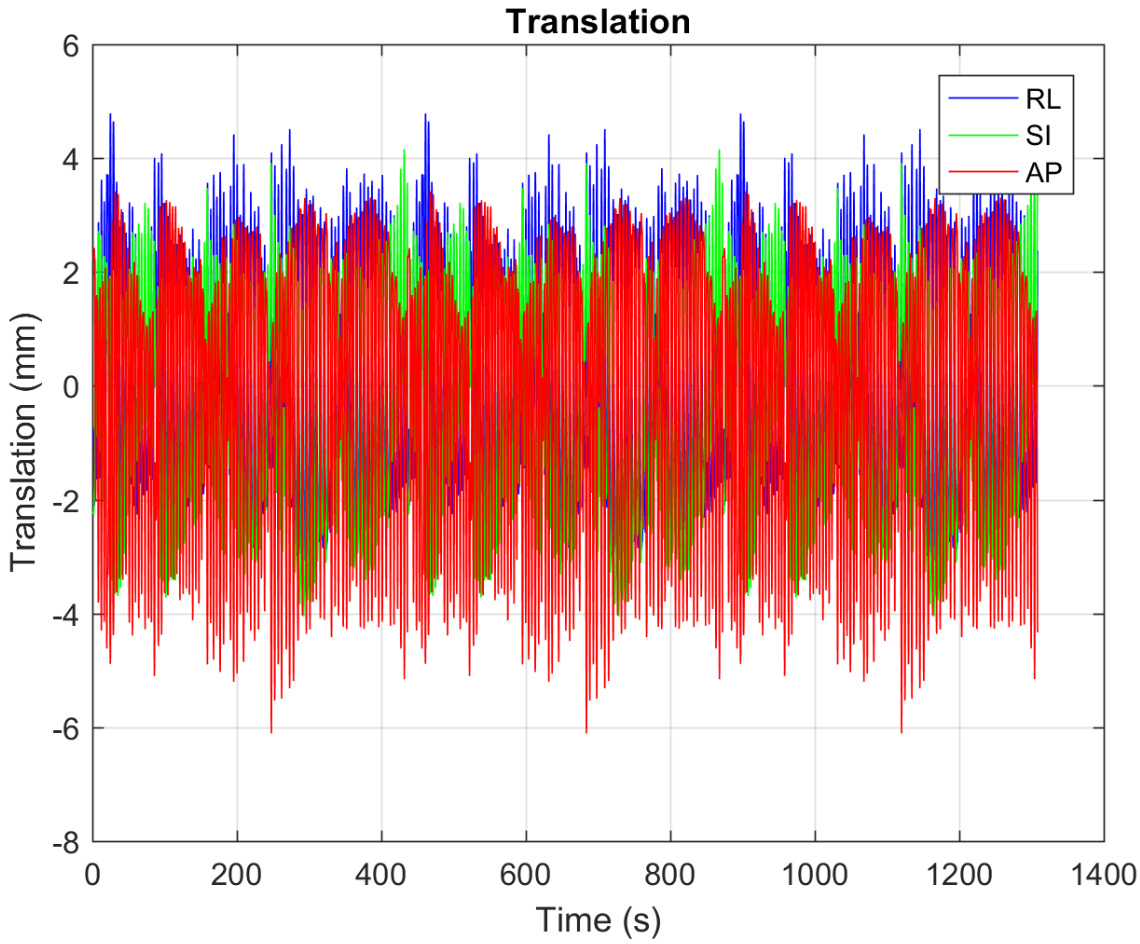


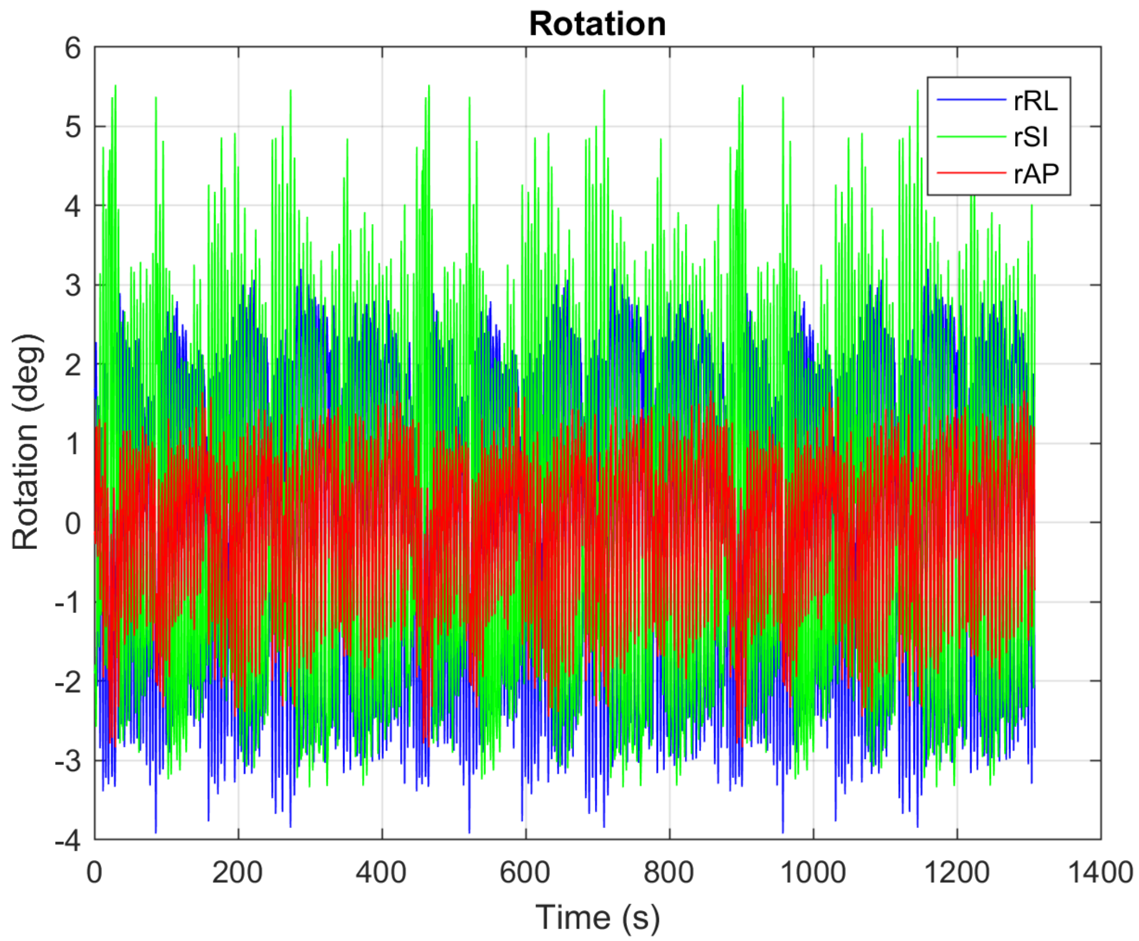
Liver: Trace 2



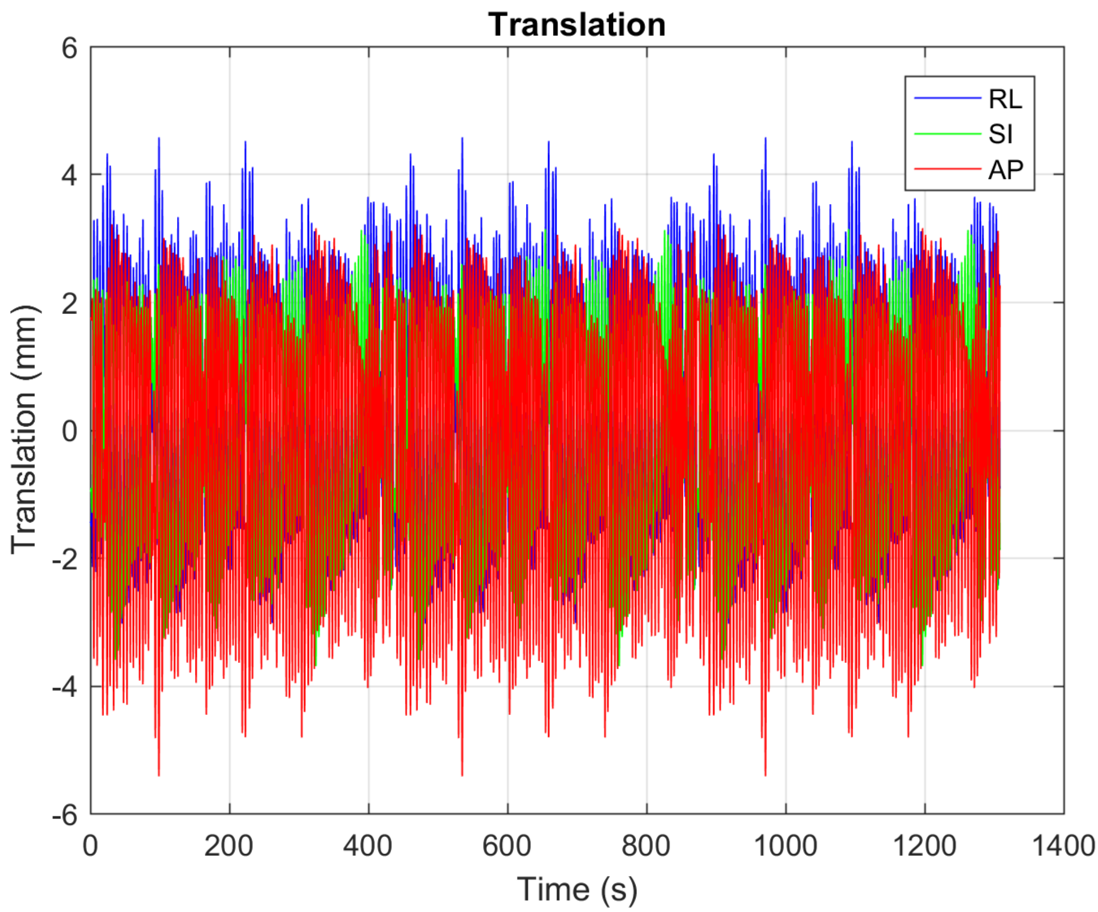


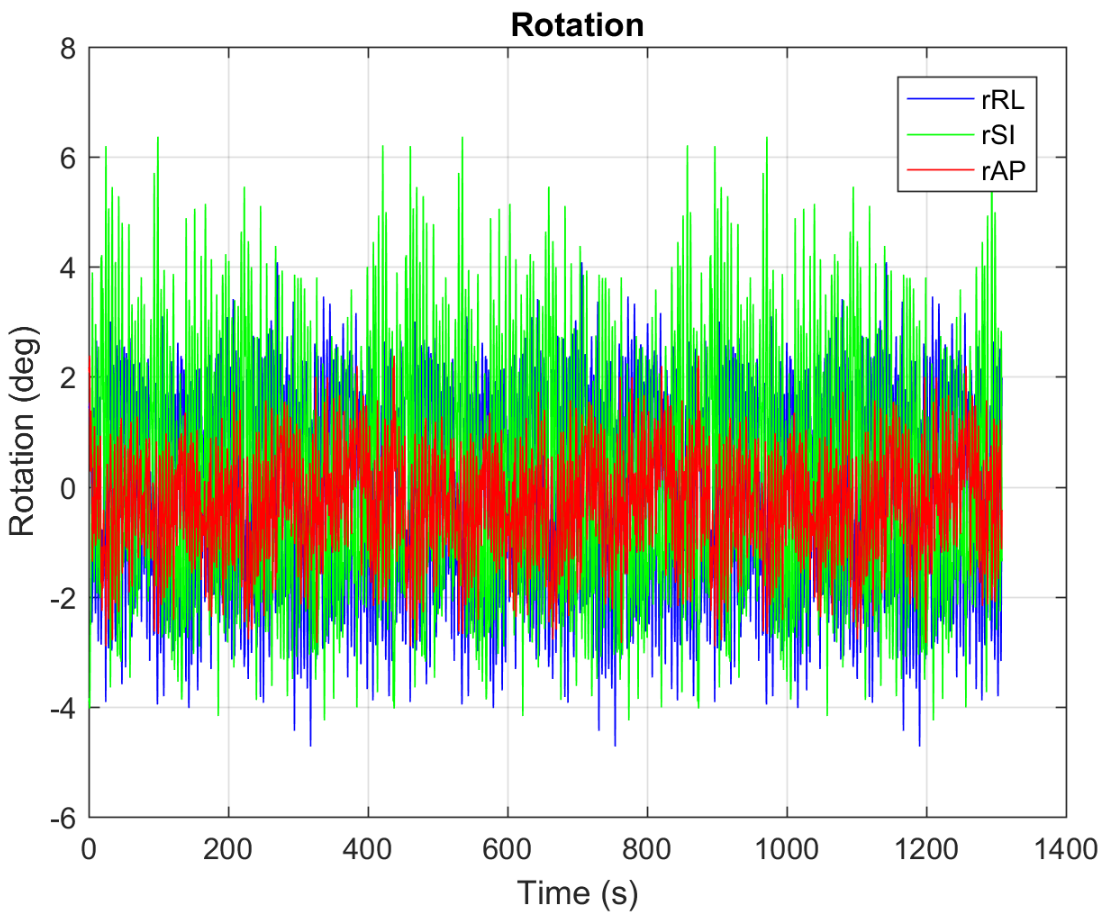
<u>Lung:</u> Trace 1 (large AP motion)





<u>Lung:</u> Trace 2 (large rotational motion (SI))





<u>Lung:</u> Trace 3 (large translational motion (SI))