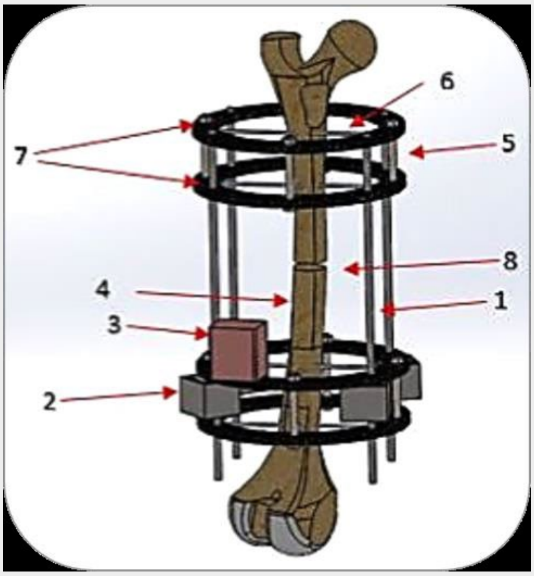
Automated Illizarov Distraction Osteogenesis

Leg Length Discrepancy (LLD) is a condition in which the paired lower extremity limbs have noticeably unequal lengths. LLDs can occur due to a variety of reasons – genetic conditions affecting growth, growth plate infections, tumors, fractures that occur through growth plate, radiation treatment from cancer etc. LLDs can be corrected by different methods but the most preferred medical procedure for correction is by lengthening the shorter limb. In limb lengthening, a surgical osteotomy is done at the bone site where distraction is intended to be performed. An external fixator surrounding the limb to be distracted is used to gradually lengthen the affected bone. The formation of the new bone directly depends on the ***rate*** and ***rhythm*** of distraction. Optimum rate of distraction is 1mm per day. Distraction of more than 2mm per day may lead to slowing down of osteogenesis, while elongation of less than 0.5mm per day can lead to premature consolidation. Rhythm of distraction of 0.25mm every six hours is acceptable. But a continuous and gradual distraction of a few micrometers at a higher frequency leading to a distraction of 1mm per day is known to yield better results.

My team and I have developed an external fixation device, which can perform precise amounts of distraction at regular intervals. The external fixation device consists of two fixation rings, which are attached to the two osteotomized bone fragments respectively. The hardware unit (which has all the electronics and the battery) controls the motors inside the gearbox, whose rotational motion causes a distraction/separation of the two different bone fragments due to a resulting translatory motion of the lead screws. The amount of distraction/separation and the intervals of distraction can be programmed through a mobile application.



1	Lead Screw
2	Gearbox
3	Electronics with battery
4	Bone
5	Connecting bolt
6	Kirschner wire
7	Fixation rings
8	Distraction region

To achieve precise amounts of distraction, we need a robust position control algorithm. We have used a novel control algorithm called “Experience Mapped Predictive Controller” (E.M.P.C) which has been developed in our lab for precise motor position control. The “Experience Mapped Predictive Controller” is inspired by the human’s ability to predict a certain behaviour/occurrence based on a past experience. It has also drawn inspiration from the human’s ability to correct their predictions by taking into consideration the various external factors which tend to result in deviations from predicted behaviours.

As a corollary, the E.M.P.C has two phases – the ‘*learning*‘ phase and ‘*control*‘ phase. The learning phase is required for the algorithm to understand the system in hand. The control phase is the predictive output of the learnt system, while adapting to the non-linearities present within the system. For our device, the learning phase consisted of providing P.W.M pulses of varying durations as an input to the motor, and creating a database consisting of the pulse duration called T_{ON}, the motor position reached at the falling edge of the pulse called P_{ON}, and the final motor settling position called $P_{SETTLING}$ (the motor tends to continue its motion, even after the pulse input is removed, due to its inertia, and finally comes to a halt). The motor positions are recorded with the help of an encoder.

LEARNING PHASE –

The video link shows the learning phase where different P.W.Ms are given to a motor for a 25kg load system. The database created looks something like this –

T_{ON} (milliseconds)	P_{ON} (raw encoder reading/pulses)	$P_{SETTLING}$ (raw encoder reading/pulses)
2	0	0
3	2	3
4	5	7
……	……	……
……	……	……
196	100	103
198	104	109
200	120	124

EMK

We call this data base as Experience Mapped Knowledge base (EMK). According to our design, 12000 encoder readings = 1mm of distraction. Hence, if a user gives a certain input for the amount of distraction required in mm, we can calculate the number of encoder pulses required to reach the position, called ‘*Demand*‘.

<u>CONTROL PHASE –</u>

The control phase is split into two parts – the Time Based Control and Position Based Control.

Time Based Control (TBC) –

The system is controlled by predicting the required time T_{ON} of the P.W.M input for the
desired output utilizing EMK. Using the EMK, we can predict the P.W.M pulse duration required to reach the Demand (D) using simple interpolation formula –

$$Predicted\ T_{ON} = \frac{(T_{ON}2 - T_{ON}1) * (D - P_{SETTLING}1)}{(P_{SETTLING}2 - P_{SETTLING}1)} + T_{ON}1$$

Where D is desired demand, $T_{ON}1$and $T_{ON}2$are the corresponding control values for $P_{ON}1$ and $P_{ON}2$ respectively
such that $T_{ON}2 > D > T_{ON}1$.

Position Based Control (PBC)–

We consider another control parameter to achieve better response even in the presence of slight parameter variations. The system is controlled by predicting the required position P_{ON} for the desired output utilizing EMK. Using the EMK, we can predict the position required be reached to reach the Demand (D) as the motor settling position using simple interpolation formula –

$$Predicted\ P_{ON} = \frac{(P_{ON}2 - P_{ON}1) * (D - P_{SETTLING}1)}{(P_{SETTLING}2 - P_{SETTLING}1)} + P_{ON}1$$

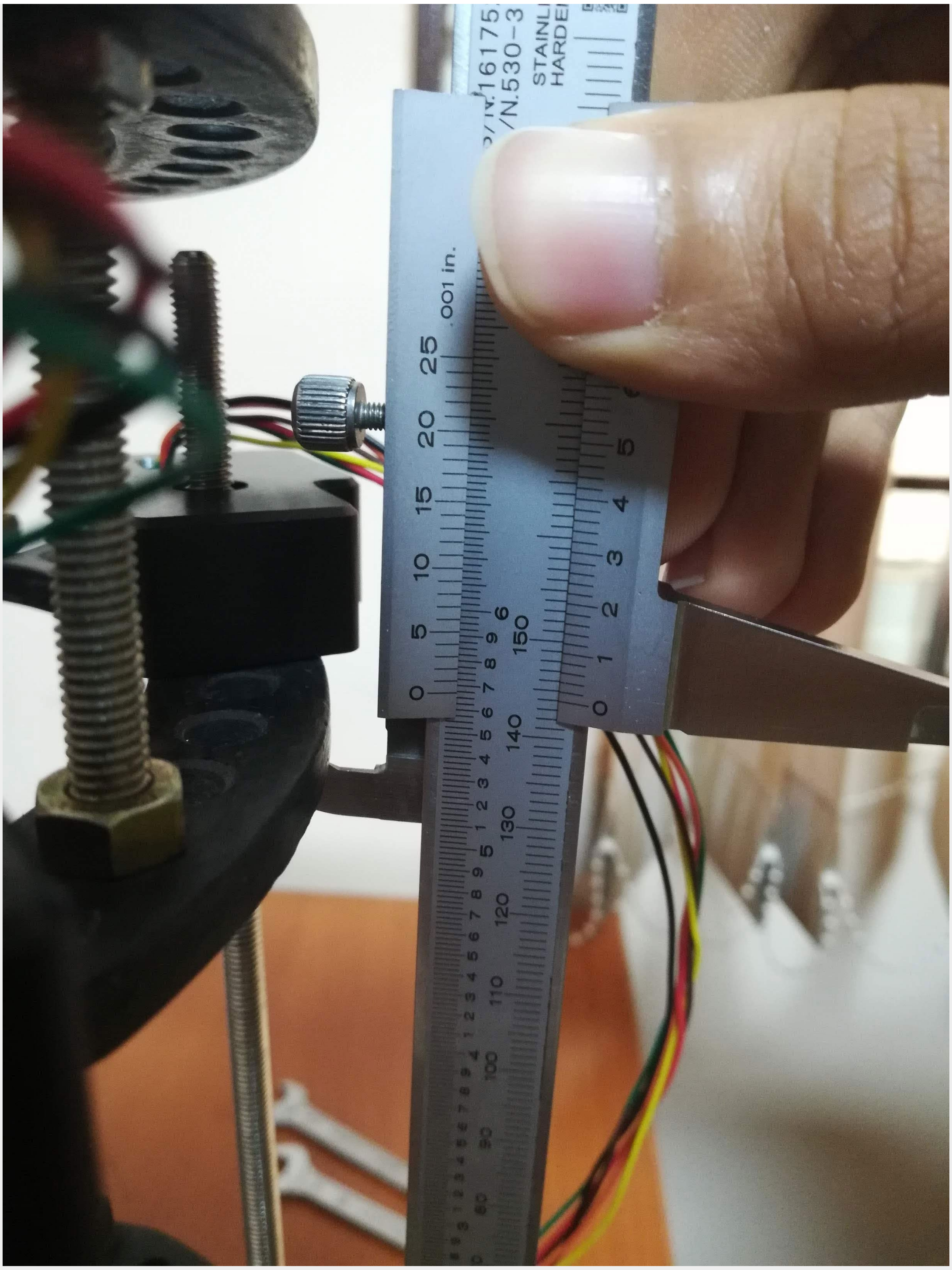
Where D is desired demand, $T_{ON}1$and $T_{ON}2$ are the corresponding control values for $P_{ON}1$ and $P_{ON}2$ respectively such that $P_{ON}2 > D > P_{ON}1$. The advantage of TBC over PBC is mainly seen in achieving zero error and for small demands. The discrete feedback provided by the encoder becomes a deterrent in using PBC when the predicted value P_{ON} for the required output is in fractions. Whereas PBC works better for larger demands. As a rule of thumb, we switch over from PBC to TBC when the error is ±12 % of Demand.

ADAPTATION –

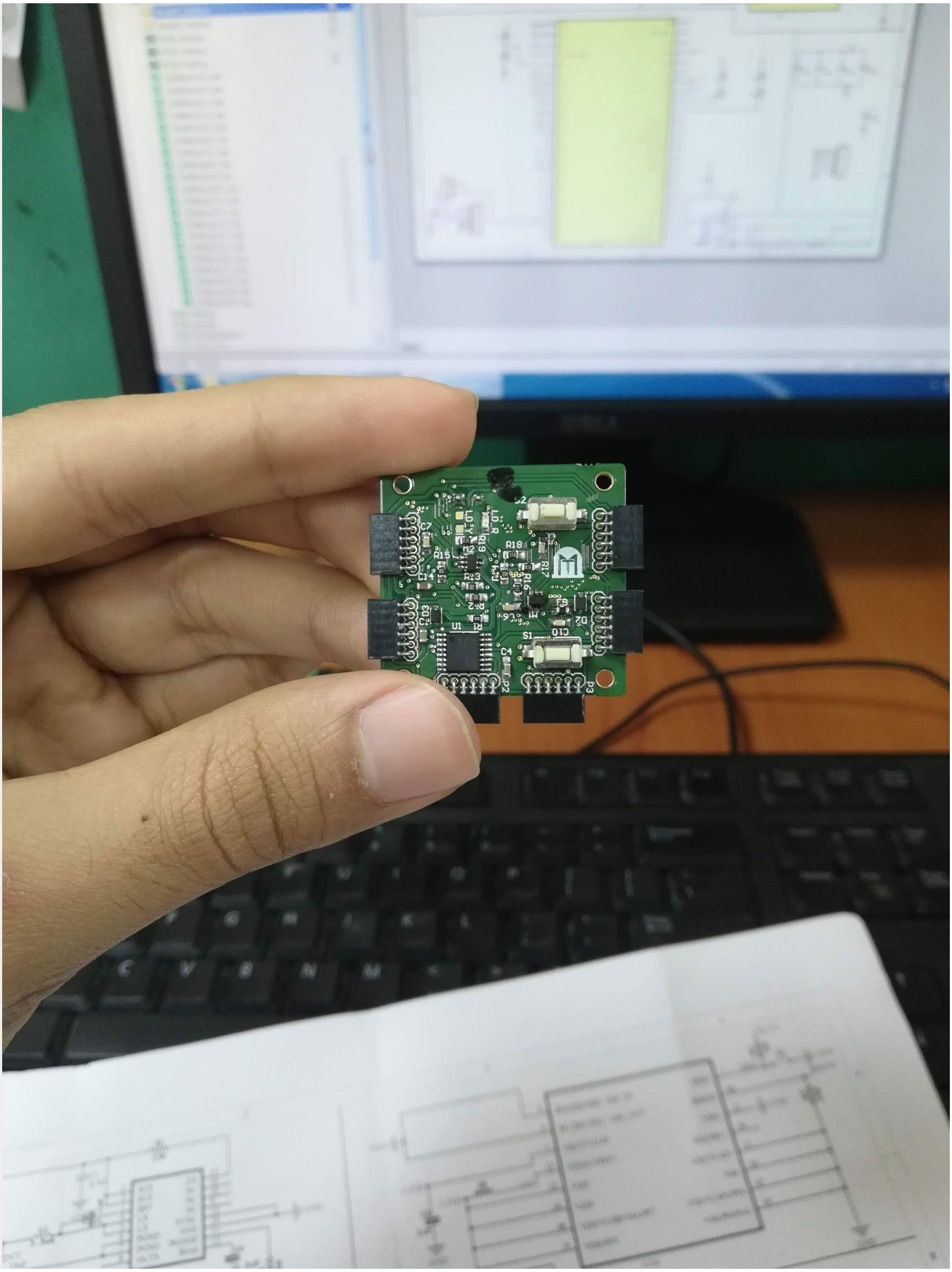
To account for the variations and the non-linearities present in the system, we introduce a factor called **Parameter Correction Coefficient** (PCC). The parameter correction coefficient is required to compensate for the system non-linearities. The PCC value is equal to the ratio of the desired Demand given as input to the final encoder reading reached for the desired demand . Suppose there is an overshoot from the desired Demand, the PCC value is less than unity. On the flip side, if there is an undershoot from the desired Demand, the PCC value is more than unity. Now, PBC and TBC are multiplied by the PCC to scale the inputs accordingly. Hence, even if there are non-linearities present in the system, such as load variations, the algorithm is able to adapt itself to the changing environment. Hence it is an adaptive non-linear controller.

TESTING AND PICTURES

A Video on Load Testing – The Fixator is able to easily handle the 100 kg load



Precise – An error of ± 1 % was achieved!



My PCB Designs!

RESULTS

Without Adaptation vs With Adaptation (No Load Variation)

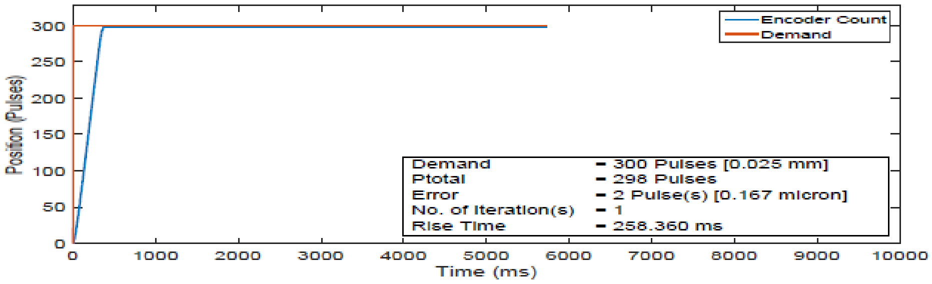


Figure: Without Adaptation

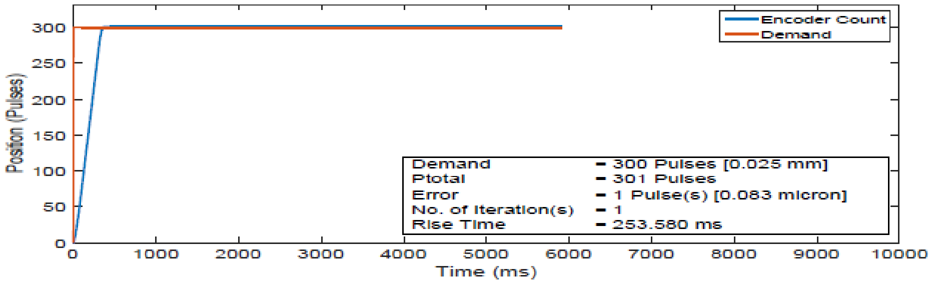


Figure: With Adaptation

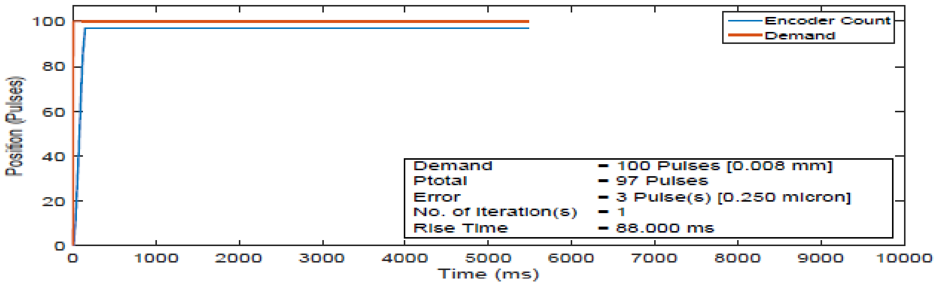


Figure: Without Adaptation

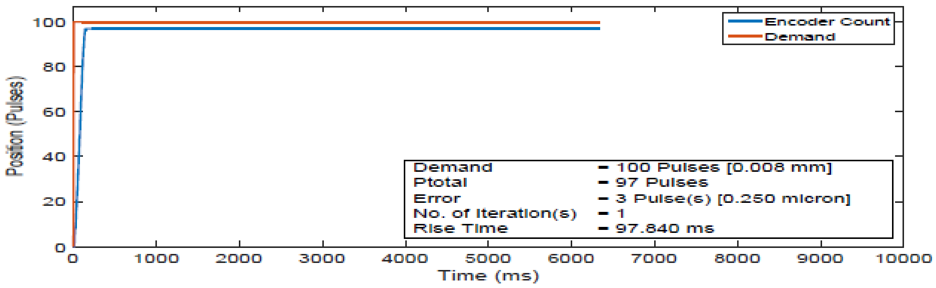


Figure: With Adaptation

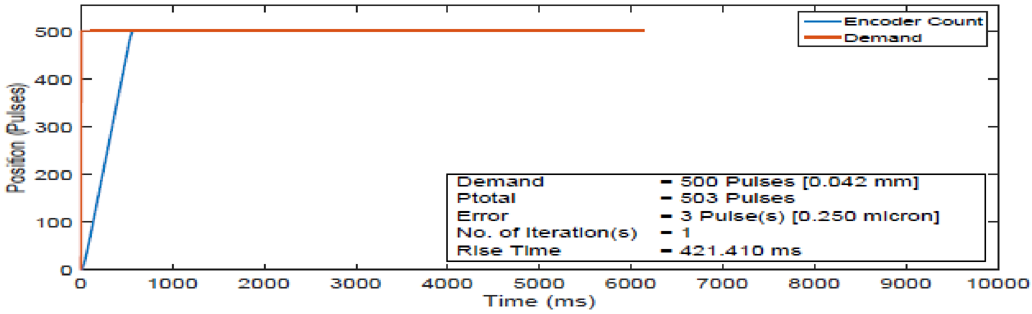


Figure: Without Adaptation

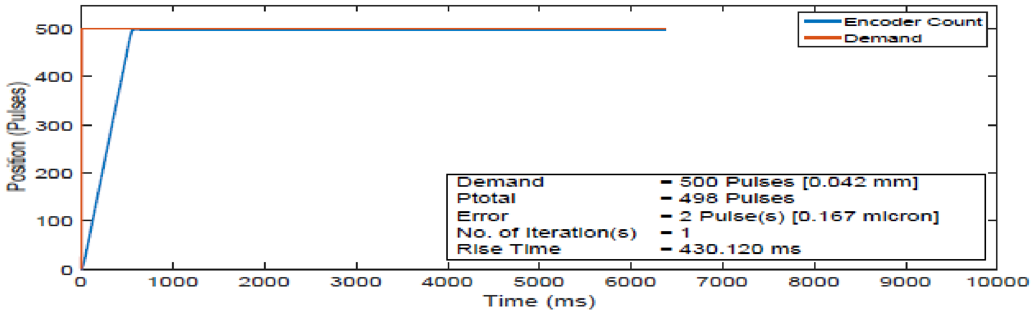
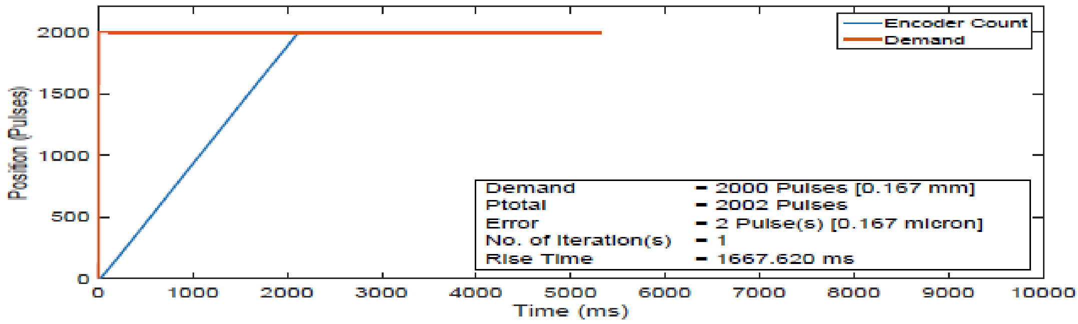


Figure: With Adaptation



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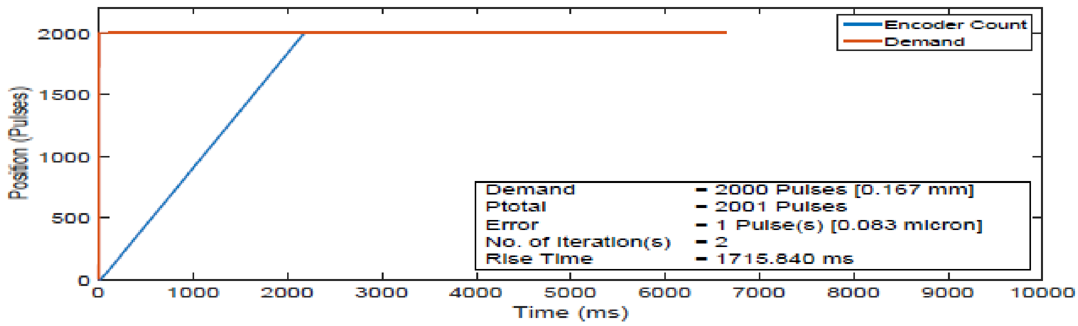


Figure: With Adaptation

Without Adaptation vs With Adaptation
Load = 60% of the Learning Load (0.6 kg-cm) EMK is developed for 1 kg-cm

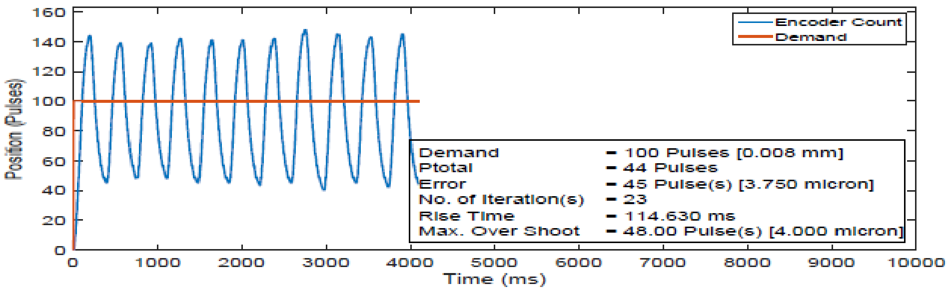


Figure: Without Adaptation

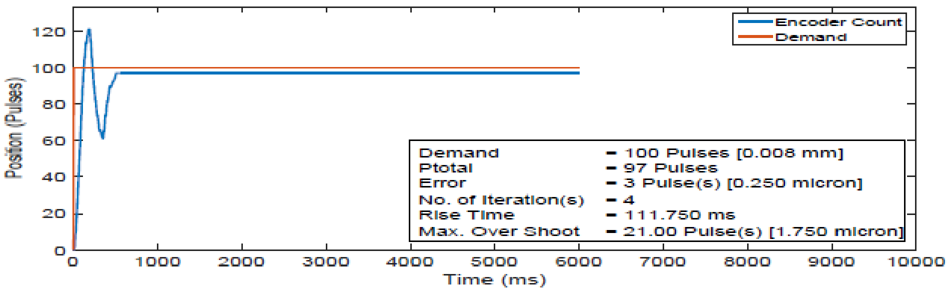
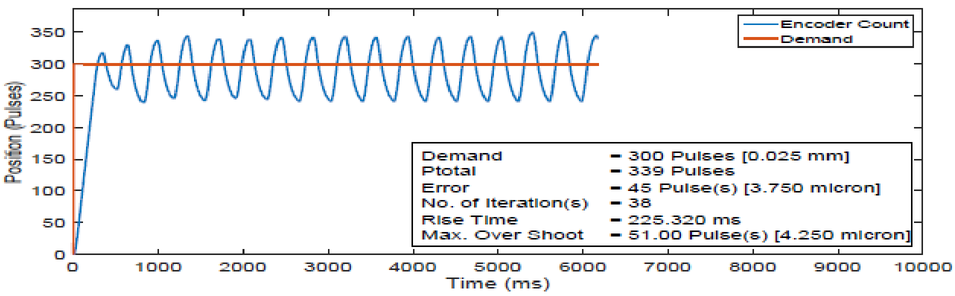


Figure: With Adaptation



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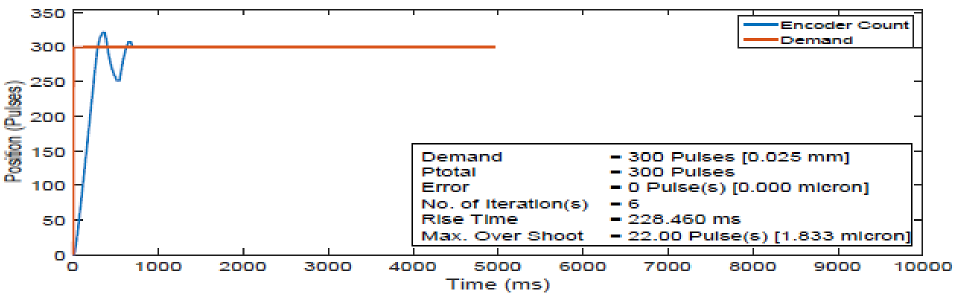

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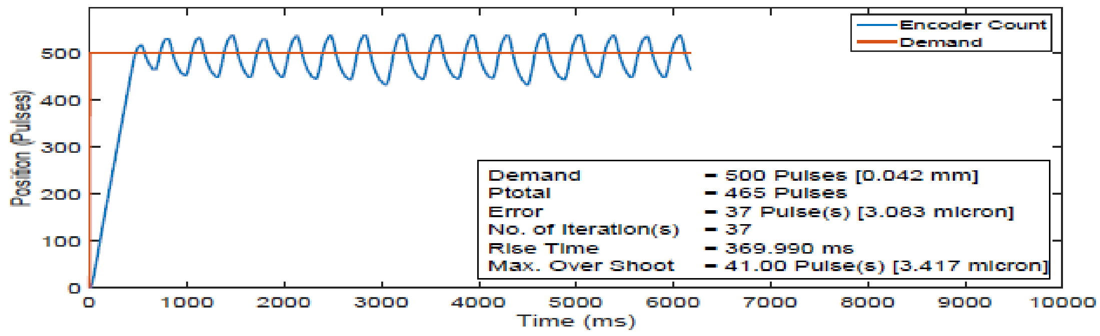

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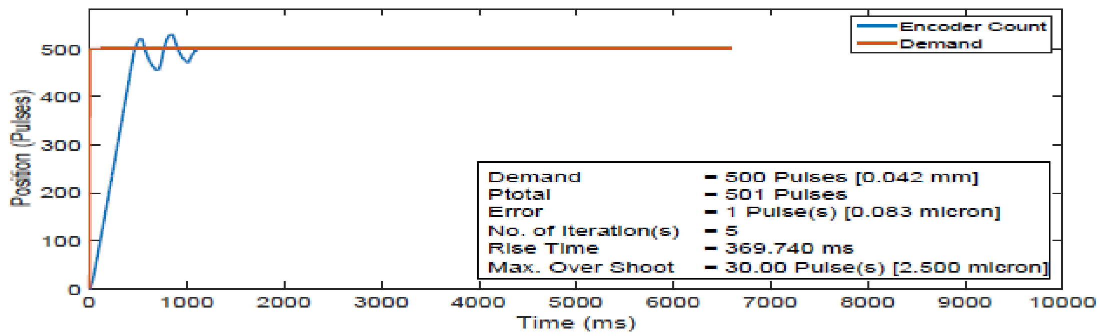

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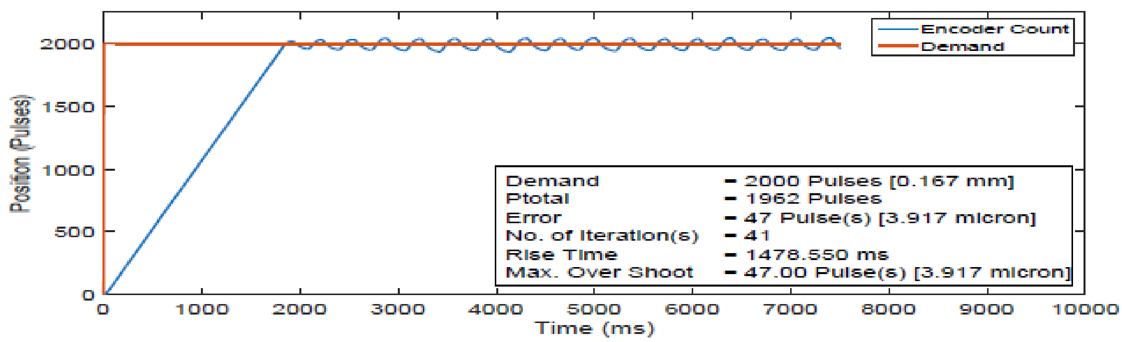

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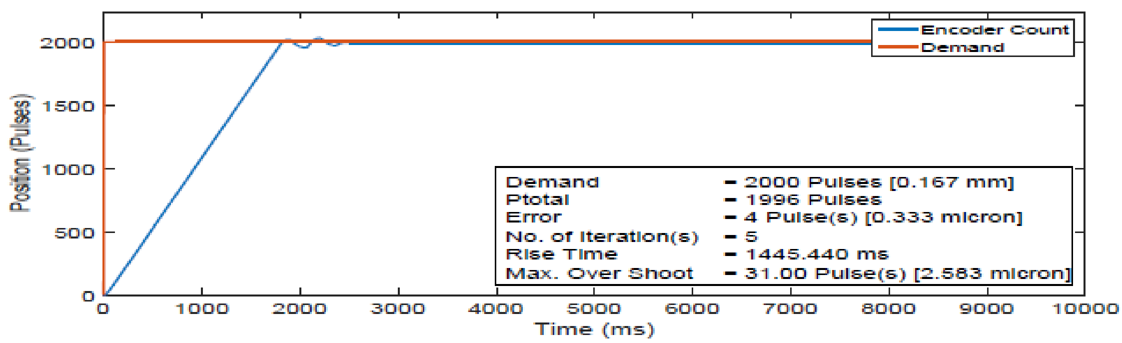

Figure: With Adaptation

Conclusion

As the results show, the E.M.P.C algorithm works well for both the cases of with or without adaptation when there is no load variation. But under changing load conditions, the E.M.P.C with adaptation proves to be superior. This novel control system algorithm works better than other adaptive control algorithms such as MRAC [1].

Illizarov external fixator is a versatile fixation system used for bone deformation correction and osteogenesis. Distraction osteogenesis for limb lengthening is carried out for over a period of 90-120 days depending on the overall length to be distracted. This is initially carried out by trained medical professional and then the patients are trained to conduct the distraction themselves, leading to a subjective dependency. To allow for better and efficient treatment, motorized distraction system has been developed which can distract the bone periodically at the desired rate without patient's intervention. A low power system has been developed, which provides a user friendly interface with any Smart Phone, using which the doctor can set various parameters including rate of distraction, rhythm of distraction, total amount of distraction etc. The system also logs the progress of the distraction procedure. The system is equipped with an emergency stop button which when pressed, aborts the distraction process.

References :

1. Saikumar, N., & Dinesh, N. S. (2012). *Position control of DC motors with Experience Mapping based Prediction Controller. IECON 2012 – 38th Annual Conference on IEEE Industrial Electronics Society.* doi:10.1109/iecon.2012.6388869
2. Aravind, M.A., Dinesh, N.S. & Rajanna, K. Adaptive experience mapping based predictive controller for under-damped type 1 systems. *Int. J. Dynam. Control* **6,** 1719–1736 (2018). https://doi.org/10.1007/s40435-018-0396-0.