AC magnetic field detection system applied to motion tracking

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Abstract

In the context of motion tracking and virtual reality, there is a strong need for sensors to monitor the motion of a moving object. These sensors are characterised by their performances (ranges, accuracy, drifts, and susceptibility to the ambient environment) and embedded (small size, light weight). The magnetic technology compared to the mechanical or optical solution allows the working without structural skeleton composed of links interconnected by monitored joints and with possible optical shadows. The principle of an AC magnetic field detection system is to generate an AC magnetic field with a reference coil (generally in the stationary frame), and to receive the signals with a sensing coil (generally in the moving frame). The analysis of the signals received allows retrieving the position of the sensing coil with reference to the emitting coil. This detection technique comes with the need of ultra low-noise and mixed-signals electronics to receive and sample the signals, and power electronics to generate the AC magnetic field. It also requires the use of small size emitting and sensing coils. In the frame of the SURGIMAG project supported by the French global competitive cluster MINALOGIC, Cedrat Technologies has developed the electronics and the magnetic transducers to complete such a detection chain. A 6 DOF (Degrees Of Freedom) AC magnetic field detection system is presented in this paper.

1 Introduction

1.1 Problematic

Motion tracking can be applied to any domain where virtual reality can be needed, such as robotic arms positioning, video games, body motion tracking, animation movies, motion analysis, 3D scanning. These systems are characterised by several parameters [1]:

- The sensor noise and its resolution,
- The accuracy/drift and repeatability
- The measurement rate and latency

Based on these requirements, several technologies can be used to design a motion tracker. The magnetic technology has advantages over the other technologies that can be applied to motion tracking, such as optical methods, or structural skeleton composed of links interconnected by monitored joints [1]. With the magnetic solution there are no issues with shadowed areas as encountered with optical solutions. There is no need for a complex moving mechanical structure, meaning no mechanical wear, leading to longer life time and better reliability. Also because of the small-sized sensors, it can be easily integrated on the final system.

Compared to DC magnetic field detection, AC magnetic field detection is immune to the ambient magnetic environment. In addition, less current is necessary to drive the coils. This leads to the use of smaller coils, smaller power amplifier, and overall lower power consumption, which is an issue for embedded applications. As a drawback, AC magnetic trackers are affected by the distortion of the magnetic field in the presence of Ferromagnetic metals. Algorithms can be applied to reduce the eddy current effects. On the **Figure 1.1**, several magnetic transducers are compared in respect of the range and the minimum detectable sensibility.

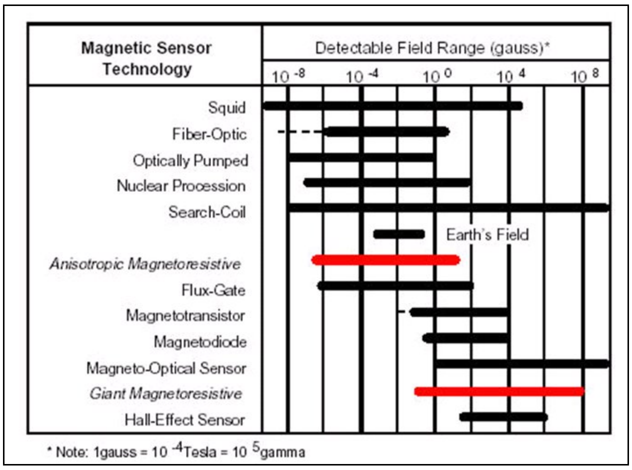

Figure 1.1 Magnetic sensor technology field range.

Due to lower cost and wider range of field detection, the solution of the search coil transducer was selected.

1.2 Concept

In an AC magnetic detection system, a reference transducer (not moving) is emitting a predetermined AC magnetic field. This magnetic field is received by a sensing transducer (moving). Knowing the emission signal, the analysis of the received magnetic field permits to retrieve the position of the sensing transducer relative to the reference [2]. To multiply the DOF (Degrees Of Freedom) of the detection system, the transducers include several orthogonal coils. Detection systems from 1 to 6 DOF can be constructed. In this paper the focus is on virtual objects having 6 DOF, three translations and three rotations. A schematic view of the 6 DOF of the transducer is given on **Figure 1.2**.

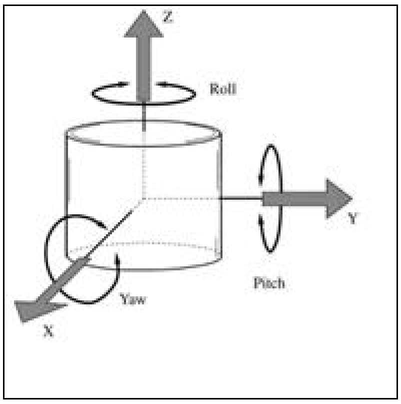

Figure 1.2 Schematic view of the 6 DOF of the transducer.

1.3 Architecture of the system

A 3-channel current amplifier is used to drive the 3 coils of the reference transducer. The supervisor sends the orders to the current amplifier through digital bus. The orders have multi-frequency content, and they are different for each of the 3 coils (axis), so that the axis can be distinguished at reception by synchronous demodulation.

At reception, the transducers are connected to an ultra-low noise conditioner that produces a voltage output depending on the magnetic field received on the coil. A high resolution ADC is used to sample the signals from the conditioner. The sampled signals are then sent to the supervisor through digital bus.

A supervisor such as a FPGA is necessary to synchronize all the elements of the detection chain. This supervisor sends the orders to the power amplifier through the digital bus, and reads the signals from the sensing coils after the sampling. It performs a digital lock-in amplification algorithm to extract the amplitude of the signals received on each receiving coil from each emitting coil. The lock-in amplification allows:

- To eliminate the 1/f noise because at higher frequency the electronic noise is only characterised by the electronic white noise.
- To select the signals received from each axis of the emission transducer with the modulation frequency.

In the case of a single emitter, for each receiving coil, 3 lock-in amplifications are performed to extract the amplitude of signal received on the coil from each of the 3 axis of the emitter. Each transducer features 3 coils, thus 9 lock-in amplification results are available to estimate the position in 6 DOF. By using the attenuation of oriented electromagnetic signals, a real-time Kalman filter estimates the absolute position and orientation of the moving transducer relative to the emitter. Kalman filters are typically used in applications that require accurate estimations of unmeasured parameters. The architecture of the complete detection system is presented on **Figure 1.3**.

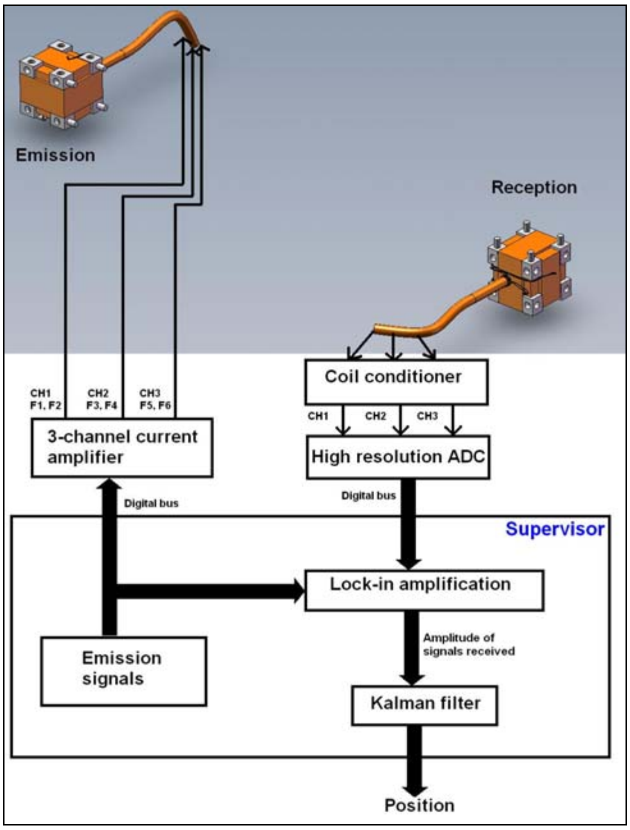

Figure 1.3 Architecture of the complete detection system.

Compared to standard AC magnetic field detection, this solution uses the redundancy of the higher frequencies to reduce the errors from the eddy currents generated in conductive materials and the performance of a lock-in amplification to detect low magnetic field to improve the overall resolution of the detection system.

Cedrat Technologies has developed the specific electronics and transducers for this application. The supervisor and signal processing are not designed at Cedrat Technologies.

2 Design of the magnetic transducers

The magnetic transducers are composed of 3 orthogonal coils that can generate or receive the magnetic field. The emitting and receiving coils are the same, so that the system can be easily reversed. The design of the magnetic transducer is a tradeoff between sensitivity and size.

From the emitter point of view, the magnetic moment must be maximised, whereas the inductance and the resistance must be minimised to reduce the dissipated power inside the coil and inside the amplifier. From the receiver point of view, the maximum flux must be received and the internal resistance must be limited to be compatible with ultra low noise conditioning. A small inductance at reception leads to higher electrical cut-off frequency of the coil which helps reducing the latency of the system.

2.1 Modelling

As previously explained, the detection principle is based on the magnetic formulas of the radial and tangential components of the magnetic field (given in **Equation 2.1**).

$$H_\theta = \frac{m}{4\pi d^3}\sin(\theta)$$

$$H_r = \frac{m}{2\pi d^3}\cos(\theta)$$

Equation 2.1 Equations for the radial and tangential components of the magnetic field. With *m=NxIxA*, N the number of turns, A the area of coil, d and θ the distance and angle of reception.

To analyse these components, dipole models of the coils were built with Flux 3D software [3], as depicted on the **Figure 2.1**. The transducer features three orthogonal coils, which have three different diameters. As a consequence, the three coils were designed independently to obtain the same flux with the same current (at emission), and reciprocally (at reception). The modelling was used to determine the maximum/minimum generated/received flux to improve the resolution/accuracy of the sensing chain, while optimizing the coil’s size at the same time.

The magnetic field received decreases with respect to $1/d^3$, with d is the distance between emitter and receiver. This means that the resolution/accuracy is better near the emitter and worse when the distance increases. This means that the flux needed to be evaluated in all positions (x,y,z, and pitch, yoll and roll – see **Figure 1.2**) inside a sphere whose radius corresponds to the maximum distance between the emitter and receiver. To simplify the finite element modelling resolution, the space was divided into several areas where the worst case was studied (static and dynamic flux). More than 16200 cases were analysed.

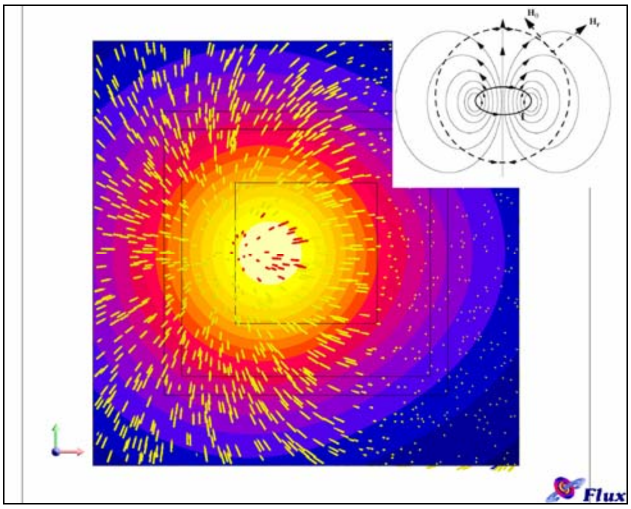

Figure 2.1 Dipole model of the coil generator and induction arrow at distance d and orientation o from Flux 3D software.

The design of the coils has been validated in simulation using the Flux 3D software. From the models, it was possible to compute the minimum flux that has to be detected to rebuild the 6 DOF with fine accuracy and resolution. This minimum flux to be detected provides specifications for the noise and the quantization of the electronics.

The design of the transducers has also to take into account the heating issues to validate the temperature at the coil’s heart. The power that needs to be dissipated when the transducer is emitting the AC magnetic field can not be neglected. The heating of the transducer was studied with the Flux 3D model. The worst case scenario is simulated, i.e. with the three coils of the transducer emitting at full-scale simultaneously.

Finally, based on the magnetic and thermal modelling results, the mechanical structure for the transducer was designed with SolidWorks, as shown on the **Figure 2.2**.

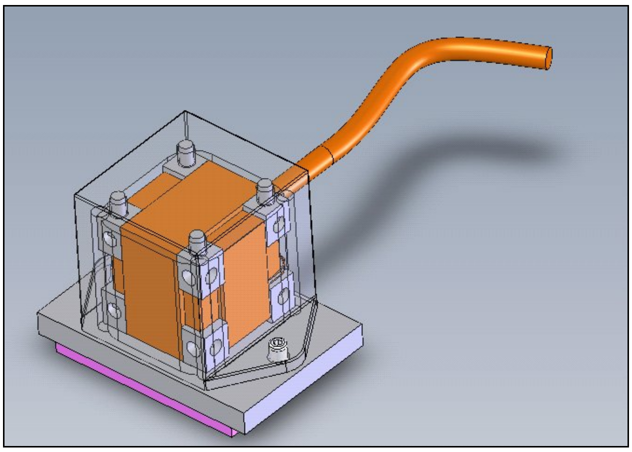

Figure 2.2 SolidWorks model of the transducer.

2.1 Manufacturing process

Two processes can be used to manufacture the orthogonal coils:

- All three coils have the same center. The 3 coils are manufactured at the same time.
- Each coil is independent, and they don't have the same center. Their assembly is done afterwards.

The first solution is better in terms of volume and regarding the estimation of the 6 DOF, but the manufacturing process is more challenging. For the 3-axis coils, a mechanical structure was designed and manufactured, and then the coils were wounded on the support with specific wires. The selected wire diameter permits to reach the performances of the model and reduces the dissipative loss for the emitter. To maximise the generated flux or the sensed flux, the solution of a ferrite core was studied. This solution was renounced due to problems for manufacturing a spherical ferrite in these dimensions and so, air coil was chosen. A 15x15x15mm transducer manufactured is presented on the **Figure 2.3**.

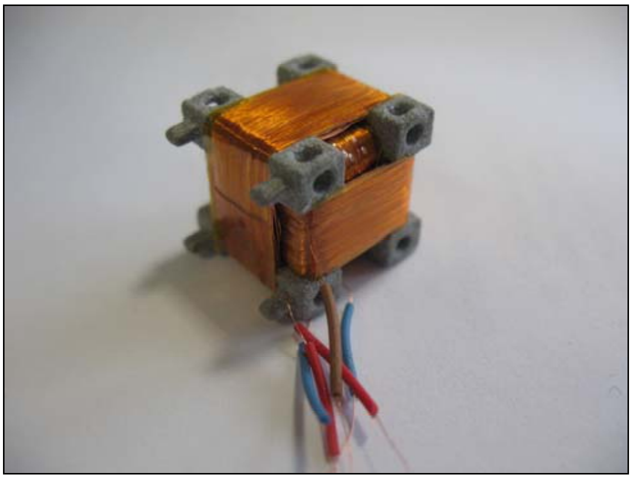

Figure 2.3 Transducer for the 6 DOF detection system.

Smaller coils could be designed, but the range or resolution would be reduced accordingly. A dedicated packaging was also designed to protect the coils from the external environment, this packaging takes into account the thermal issues previously mentioned.

3 Electronics for magnetic field detection and generation

The emission and reception of the magnetic field on the magnetic transducers requires specific electronics. The AC magnetic detection technique comes with the need of ultra low-noise and mixed-signals electronics to receive and sample the signals. Power electronics are required to generate the AC magnetic field on the coils of the transducer.

3.1 Magnetic field generation

For the generation of the magnetic field, a 3-channel linear current amplifier was designed. This power amplifier is presented on the **Figure 3.1**. A linear topology was used to achieve a high SNR, which is very important for an application where a very low-noise is required. The amplifier receives the orders through a digital bus, so that the digital supervisor can address it directly. The power amplifier offers a bandwidth of 50KHz and it can output ±50Vpk to generate a current of ±75mApk in the coils of the emitting transducer. Those values are issued from the modelling, to reach the minimum detectable flux.

Figure 3.1 3-channel current amplifier for AC magnetic field generation.

The power supply for the generation part of the detection system is designed using high frequency DC/DC converters. This power supply is shown on the **Figure 3.2**. The different DC/DC converters of the power supply are synchronized to switch at a frequency of 500KHz avoiding intermodulation issues. This solution offers high power efficiency and smaller size compared to linear regulation. The switching regulation generates noise, but 500KHz is far outside the bandwidth of the lock-in amplification output, so it will be neglectable. Linear regulation can not be used as it generates 50Hz noise which is in bandwidth of the output of the lock-in amplification.

Figure 3.2 Power supply for the generation of magnetic field.

With one power amplifier, one reference transducer can be driven. More reference transducers can be used if there are disturbances, and if redundancy is needed.

3.2 Magnetic field detection

For the detection of the magnetic field on the receiving transducer, a multi-channel coil conditioner was designed. It is an ultra low-noise conditioner, which is optimized to be matched with the transducer's impedance [5]. This coil conditioner is presented on the **Figure 3.3**. It is based on a standard trans-impedance conditioner topology.

Figure 3.3 Coil conditioner for receiving transducers.

The coil conditioner outputs a voltage representing the magnetic field sensed on the coils. For the detection chain composed of the coil and conditioner, the minimum detectable magnetic field is less than 10pT in the 50Hz bandwidth thanks to the lock-in technique.

The output of the conditioner is sampled by a high resolution ADC, represented on **Figure 3.4**. The ADC features 9 channels that are simultaneously converted and read. The resolution is 24bits, and sampling rates up to 300KSPs can be achieved. The high resolution is necessary to detect simultaneously magnetic fields from 10pT to 26µT depending on the distance and orientation between emitter and receiver. The high sampling rate allows high emission frequency (up to 50KHz in the system).

The result of the analog to digital conversion is read by the supervisor to compute the lock-in amplification.

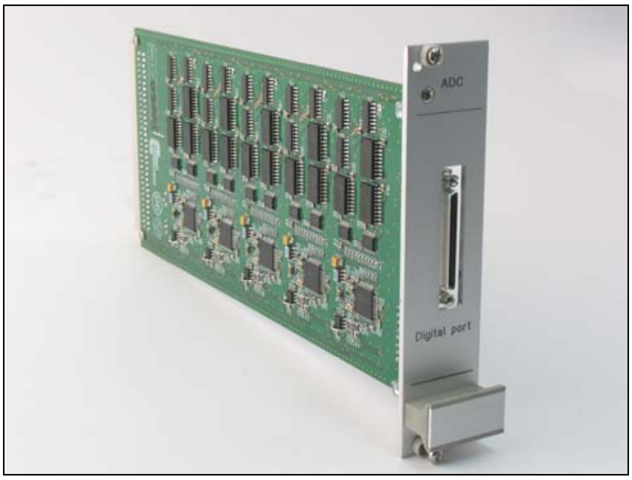

Figure 3.4 High resolution multi-channel ADC.

The power supply for the magnetic field detection is similar to the power supply used in emission, only it produces lower voltages.

Finally, two independent racks are produced. The emission rack features its DC power supply and the current amplifier. The reception rack features its DC power supply, the coil conditioner, and the ADC converter.

4 Practical tests

4.1 Objective

The objective of the practical tests was to evaluate the resolution obtained for the detection system described previously. It was already discussed that the resolution depends on the distance between the reference and the moving transducer. This comes from the fact that the attenuation of the magnetic field is proportionate to $1/d^3$ (see **Equation 2.1**) where d is the distance between the two transducers. Thus, a displacement of 200µm does not generate the same variation of sensed magnetic field if at a distance of 30cm or at a distance of 10cm.

The distance of detection targeted is 30cm, i.e. the resolution of the detection system is kept for any position of the transducer in a sphere of radius 30cm around the reference. For positions outside of the sphere, the resolution will drop.

4.1 Test setup

The test setup used to evaluate the resolution of the detection system is composed of two transducers, the first is the reference, and the second is moving. The moving transducer is placed at 30cm from the emitter as it can be seen on **Figure 4.1**. An APA (Amplified Piezo Actuator [4]), is used to generate a precise displacement of the moving transducer. An APA200M from Cedrat Technologies is used, it has 200µm stroke. A non magnetic version of the actuator is used so that there are no disturbances due to eddy current losses. A LA75A power amplifier is used to drive the piezo-actuator.

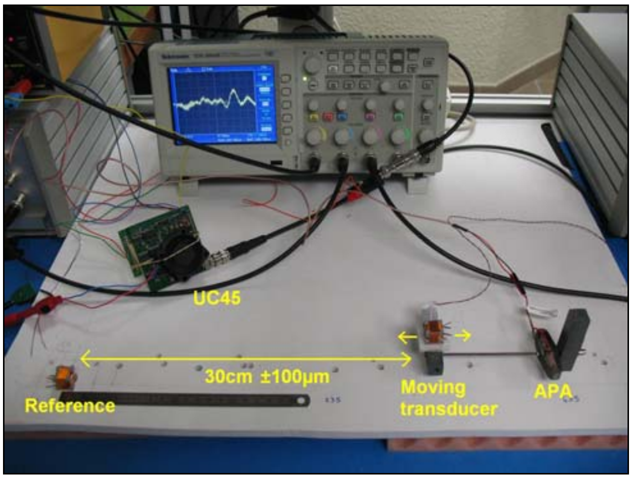

Figure 4.1 Test bench for resolution testing.

The lock-in amplification is performed by a lock-amplifier SR830 from Stanford Research Systems. It is programmed to provide an order of 75mApk at 8KHz to the current amplifier. The result of the analog digital conversion of the ADC is read by a UC45 digital controller at a rate of 60KSPs. This result is then fed to the lock-in amplifier. The time constant of the output filter of the lock-in amplifier is set to 30ms.

4.2 Test results

The result of the lock-in amplification is monitored and compared with the order to the piezo-actuator, so that it is visible that there is a correlation between the two signals. The **Figure 4.2** presents the comparison for a square order of 200µm. The **Figure 4.3** presents the same comparison but with a sine order of 200µm. On those Figures, [CH2] in blue is the output of the lock-in amplifier, and [CH3] in purple is the order of the piezo actuator.

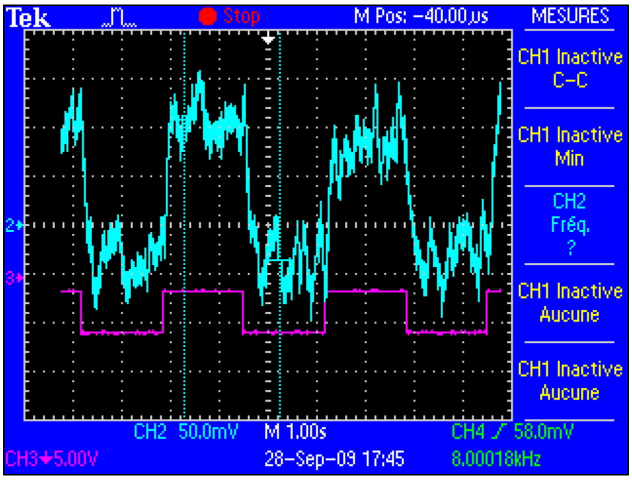

Figure 4.2 Detection of a 200µm square displacement.

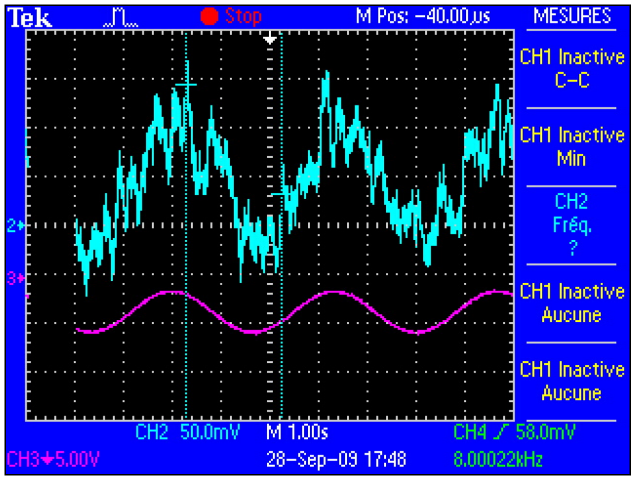

Figure 4.3 Detection of a 200µm sine displacement.

As it can be seen on the previous Figures, there is a strong correlation between the order of the actuator, and the output of the detection system. A variation of 200µm on the position of the moving transducer is visible at the output of the detection system. This means that this detection system offers a minimum resolution of 200µm on a 30cm range.

It is even possible to distinguish the shape of the sine displacement on **Figure 4.3**, which means that the resolution is actually a bit smaller than 200µm.

6 Conclusion

The specific transducers and electronics for an AC magnetic field detection system with 6 DOF were designed. Those components were carefully designed and optimized to achieve a high resolution motion tracking system. Only the supervisor with the signal processing needs to be added to complete the detection system. Through testing, it was shown that this detection system offered a resolution of better than 200µm on a 30cm detection range.

Future work focuses on the solutions to reduce the size of the transducers. This would lead to lighter and smaller detection system. The integration would be eased, and it would be possible to target more applications.

7 Acknowledgements

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8 References

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