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On the potential for Electromagnetic Energy Harvesting for a Linear Synchronous Motor based Transport System in Factory Automation

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Abstract— Transport systems incorporating linear synchronous motors (LSMs) enable linear motion at high speed for emerging factory automation applications. The goal of this work is to determine the feasibility of harvesting energy directly from an operational LSM transport system employed in high volume manufacturing. Microelectromechanical (MEMs) based sensor technology, deployed as part of a wireless cyber physical system (CPS), perform near real-time magnetic field measurement for a mobile LSM vehicle. The vehicle under study is purposed for mobile factory automation and is not wired for communications nor does it have an onboard power source. A series of experiments were designed and conducted to establish the magnetic profile of the system. Empirical data capture was conducted on a cycled LSM test-bed comprising of 2 shuttles and 2 x 3 meter lengths of LSM track (MagneMotion QuickStick®100). Varying vehicle speeds were incorporated in the experimental regime to determine how changes in velocity would impact the magnetic profile of the vehicle. The recorded magnetic field data was analysed and a relationship between LSM vehicle speed and magnetic field frequency was established. The study highlights the potential to employ a single receiving coil to enable energy recovery which in turn could power a cyber-physical system (CPS) tasked with performing condition based monitoring of the LSM transport vehicles. This in turn can form the basis for the development of a predictive maintenance system, deployed to an LSM based transport layer in high volume manufacturing environments.

Keywords— Linear Synchronous Motors, Cyber Physical Systems, Magnetic Field Analysis, Microelectromechanical Sensors, Predictive Maintenance.

I. INTRODUCTION (HEADING 1)

High speed linear motion can be enabled employing linear motors without incorporating rotational to translation conversion with gears or linkages. These linear motors are used frequently in modern transportation systems [1]. Where the moving component (vehicle) of the linear motor is propelled by a synchronous mobile magnetic field this is known as a linear synchronous motor (LSM).

LSM systems can be employed for precise vehicle movement and positioning when integrated with dynamic

control and feedback position sensing [2]. Two central components make up a typical LSM system. The primary component is generally comprised of a linearly arranged poly-phase electromagnet. An array of permanent magnets configured in an alternating manner and typically situated with the load under transport make up the secondary part of the LSM. The primary is generally static, embedded in a track and induces a travelling magnetic field in an air gap between the components to propel the vehicle.

LSM technology can be arranged as slotted or slot-less, double sided or single sided, iron-cored or air-cored [3]. There are many applications for LSMs including maglev train conveyance [3], hoist systems [4] and cable-free elevators [5]. The emergence of Industry 4.0 has enabled a number of new applications incorporating LSM transport the goal of which are to drive efficiencies and responsiveness in high volume manufacturing [6]. A concept illustration of an LSM transport layer for integration in smart manufacturing applications is shown in Fig. 1. The system illustrated is the MagneMotion QuickStick® 100 (QS 100) LSM transport system [7] and is comprised of vehicles and one meter length modules that are reconfigurable to factory process requirements. The primary component is contained in the module along with a digital controller and position sensors. The primary motor is linked via serial communications to a network where the host and node controller are located. This creates a feedback loop employed to control speed, vehicle traffic and positioning [8].

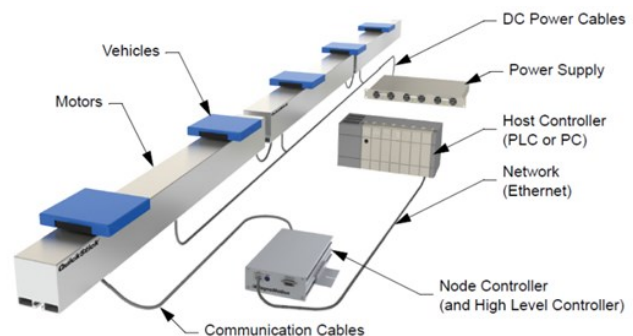


Fig. 1. Simplified View of the QuickStick 100 Transport System [7]

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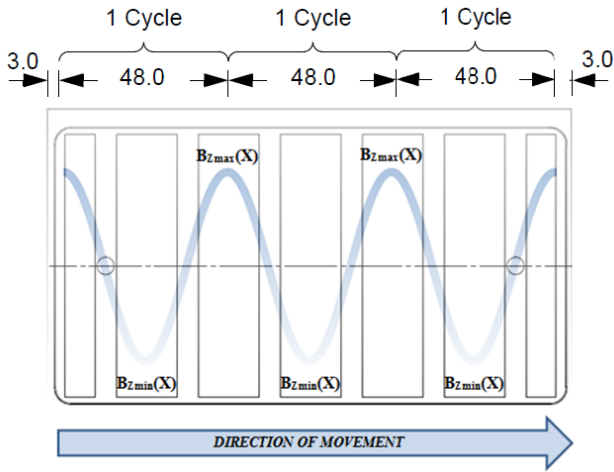


Fig. 2. LSM Magnet Array Mechanical Drawing [7]

The secondary component or vehicle is attached to a magnetic array. Magnemotion standard magnet arrays consist of magnets arranged with alternating polarity. Fig. 2 illustrates the mechanical drawing of the 3 cycle Magnemotion standard magnet array, along with a spatial representation of the vertical component of the static magnetic field [7]. The direction of travel is denoted as X and the 3-cycle sinusoidal magnetic field is represented by B_z . The interaction of this spatially sinusoidal magnetic field with the travelling magnetic field produced by the LSM motor generates linear motion for the LSM vehicle.

Each vehicle must be grounded to the guide-way employing conductive materials in the manner shown in Fig. 3. A gap of approximately 3mm is required between the motor and the vehicle magnet array. Rollers or wheels are integrated in the vehicle to maintain the spacing thusly ensuring smooth changes in velocity as the cargo is traversing the manufacturing line [8]. However these mechanical parts can wear over a period of time resulting in failure and potential losses in production time. To address this risk intermittent preventative maintenance is utilised thusly managing the probability of mechanical failure. In practice the rate of failure increases with the age of the equipment and this is accompanied with a decrease in the efficiency and reliability of maintenance scheduling. Costs to the business can as a result increase. A methodology employing sensor technology integrated in the LSM vehicle and capable of determining the condition of the vehicle at any given time could mitigate such risks and provide a basis for improved manufacturing efficiency.

Cyber physical systems (CPSs) are an enabling technology for the real-time control and monitoring of industrial equipment. CPS can be a useful tool to predict and trigger maintenance only where there is a definitive need, through remote fault detection [9]. This process is known as predictive maintenance (PM). Mechanical components including bearings [10] and milling processes [11] have been monitored by CPSs as part of practical PM methodologies. These systems incorporate microelectromechanical sensors to perform fault isolation. Wireless communications enable CPS to be deployed and operate in a distributed manner to satisfy the requirements for a broad range of industrial applications [12]. Many use cases require extended battery lifetimes for deployed CPSs to reduce maintenance overhead and associated production downtime.

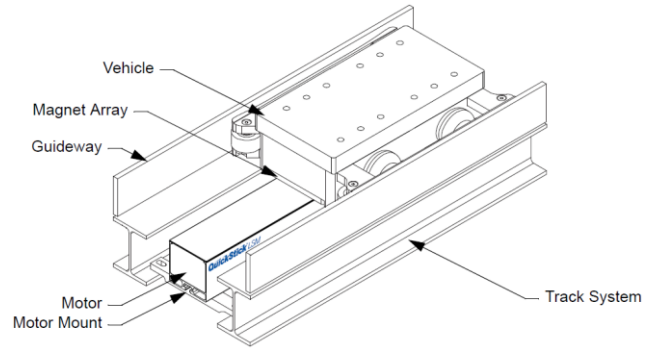


Fig. 3. LSM vehicle for QuickStick 100 Transport System [7]

The LSM vehicle under study is deemed passive in that there is no cabling to implement communication to the primary backbone nor is an onboard power source available. For this reason, any proposed CPS sensing technology when integrated in the vehicle is required to be wireless and battery powered. The high volume production line in J&J Vision Care runs for extended periods therefore minimal opportunity is afforded for recharging or replacing batteries for the proposed CPS following integration in the LSM vehicle. Energy harvesting affords the possibility of extending operational longevity for CPSs [13]. Previous research in energy harvesting has suggested there is potential for returns in low frequency time varying magnetic fields [14]. However an empirical assessment of the potential to recover energy directly from the low frequency magnetic field, generated as an LSM vehicle is propelled through the manufacturing process, has to the authors knowledge not been reported.

The goal of this work is to experimentally establish the feasibility of such an energy recovery system. The harvested energy could in turn be employed to supplement the power source for a CPS, tasked with performing PM for the LSM vehicle under study. An electromagnetic energy harvesting implementation of this nature employs an inductive coil and associated energy management circuitry [13]. To enable a viable energy recovery implementation a number of key criteria must be met. Firstly the presence of a time varying magnetic field must be established and must exhibit magnitude and frequencies in a suitable range so as to make energy recover possible [15]. In addition a number of factors can significantly increase implementation difficulty and reduce potential power returns. For example multiple interfering and/or cancelling magnetic flux sources can result in a requirement for a complex array or configuration of coils [16].

The paper is organized in the following manner. Section II provides an overview of the problem formulation for the magnetic characterization proposed as part of this work. A description is included of the CPS implementation designed to capture and wirelessly transmit magnetic information from the mobile LSM vehicle to a central repository. An explanation of the LSM vehicle instrumentation methodology is provided, along with an overview of the experimental test-bed and methodology. In section III the experimental methodology is presented along with empirical results captured from the QS 100 test-bed. A discussion surrounding the key findings is detailed. Conclusions and future work are included in Section IV.

II. METHODOLOGY

A. Magnetic Field Characterisation: Problem Formulation

Magnetic flux is a measurement of the total magnetic field which passes through a given area and can be represented as follows:

$$\Phi_B = \int_S \mathbf{B} \cdot d\mathbf{S} \quad (1)$$

According to Faraday's law, the voltage induced on a receiving coil is proportional to the time variation of the magnetic flux [17]:

$$V = - \frac{d\Phi_B}{dt} \quad (2)$$

As mentioned previously the goal of the characterisation is to assess the potential for magnetic energy recovery as part of the development of a vehicle CBS platform. Considering equations (1) and (2) the following hypotheses are posed and experimentally examined within the context of this study so as to establish the feasibility for energy harvesting:

1. *Time Varying Magnetic Field*: A time varying magnetic field denoted $\frac{dB}{dt}$ is present during LSM vehicle movement, such that an accompanying varying electric field is generated, in which a coil can be orientated to recover energy.
2. *Magnetic Field Magnitude and Frequency*: Magnetic field B and frequency f_B is of sufficient magnitude so as to enable the development of supporting energy management circuitry.
3. *Magnetic Field Frequency relation to LSM Vehicle Velocity*: A relationship between magnetic field frequency f_B and LSM vehicle velocity $v_{vehicle}$ exists such that any subsequent proposed energy recovery methodology can be made to function and generate power at varying vehicle velocities.
4. *Non-Cancelling Magnetic Flux*: A uniform non-cancelling magnetic flux is present, spanning the magnet array, enabling the use of a single receiving coil in an energy harvesting implementation. This in turn identifies regions of equal sign for $\frac{dB}{dt}$ so that the terms in equation (2) add to one another.

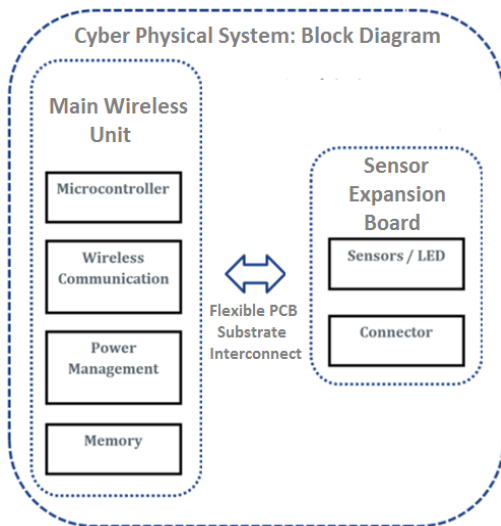


Fig. 4. CPS Sensor Platform Block Diagram

TABLE I. CPS WIRELESS SENSOR PLATFORM SPECIFICATIONS

Parameter/Component	Specification
MCU RAM	2 MB
MCU FLASH	256 KB
MCU Speed	Max 180 MHz
MCU Core	ARM® Cortex®-M4-based 32 bits architecture
MCU Other	Built-in Single Precision Floating Point Unit
Wireless Main Unit	Wireless Protocols
	Wi-Fi: IEEE 802.11 a/b/g/n
	Wireless Protocols
	Dual mode 4.0 (Classic and BLE)
	Wireless Throughput
	MCU@56 MHz & Wi-Fi 4.4 Mbps
	Onboard Memory
	EEPROM 512KBIT
	Battery & Charging
	Standard Li-ion / Li-Polymer
Sensor Expansion Board	Inertial Sensor
	MPU 9250
	3-axis Accelerometer
	3-axis Magnetometer
	3-axis Gyroscope

B. Cyber Physical System Wireless Sensor Platform

To facilitate the capture of the magnetic profile of the LSM system a lithium ion powered wireless CPS platform has been implemented. Fig. 4 illustrates the block diagram of the CPS platform. The core technology outlined in Table I is integrated in the main wireless unit. Edge processing is enabled with a 32 bit microcontroller with floating point hardware unit and a digital signal processing core. The platform is both WiFi and Bluetooth Low Energy compliant enabling low end to end latency achieving throughput speeds of up to 4.4 Mbps.

USB connectors interface the main wireless unit with the plug-in expansion sensor boards. Up to 5 sensor boards can be interfaced in tandem. Flexible printed circuit board (PCB) substrate interconnects the USB sensor board interface with the sensing component as illustrated in Fig. 5. This flexibility allows remote locations to be instrumented where minimal clearance is available. The expansion board has an integrated microelectromechanical (MEMs) based inertial sensor (the MPU-9250 from InvenSense). The package contains a 3 axis magnetometer employed in this study to gather magnetic field information for the LSM system.

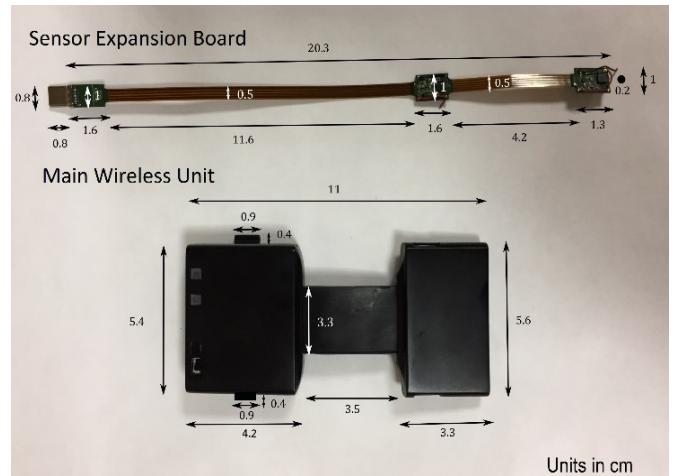


Fig. 5. CPS wireless sensor platform housed highlighting the flexible PCB substrate interconnect.

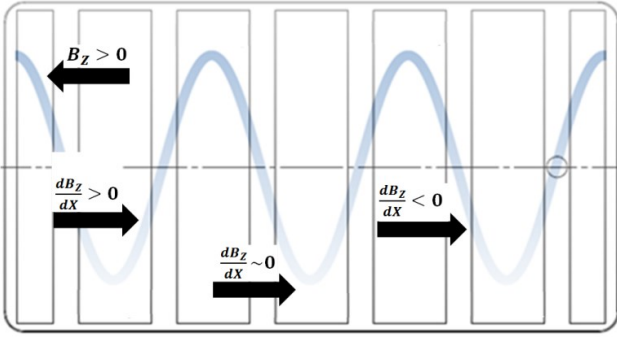


Fig. 6 Instrumentation of the vehicle

C. LSM Vehicle Instrumentation

The vehicle was instrumented with sensor expansion boards at the locations highlighted in Fig. 9. To assess the polarity of the magnetic flux in (2), the sensor locations were determined to account for regions that cover a wide variety of boundary conditions and 2 complete cycles of the magnet array. The selected boundary conditions are summarized in Table II.

D. QS100 Experimental Test-Bed

The data capture was conducted using an experimental test bed designed and built by J&J Vision Care in partnership with Modular Automation. Magnemotion QuickStick 100 linear motors provide the backbone of the system with custom guidrails and rollers, similar to those seen in Fig. 3. The experimental setup replicates the LSM system found in J&J with parallel LSM lines of 3m length and vehicle shuttles at either end which distribute the vehicles between the parallel tracks. The layout for the test-bed is illustrated in Fig. 7.

The test bed allowed like for like comparison of data gathered with production conditions in J&J Vision Care, complete with like for like Rockwell/Allen Bradley PLCs and control architecture seen in the industrial setting. This allowed the efforts to design the experimental test to plan for the expected conditions upon implementation in a production setting.

TABLE II. VEHICLE INSTRUMENTATION BOUNDARY CONDITIONS

Region	Boundary conditions	
1	$\frac{dB_z}{dX} \sim 0$	$B_z(X) < 0$
2	$\frac{dB_z}{dX} < 0$	$B_z(X) > 0$
3	$\frac{dB_z}{dX} > 0$	$B_z(X) < 0$
4	$\frac{dB_z}{dX} < 0$	$B_z(X) < 0$

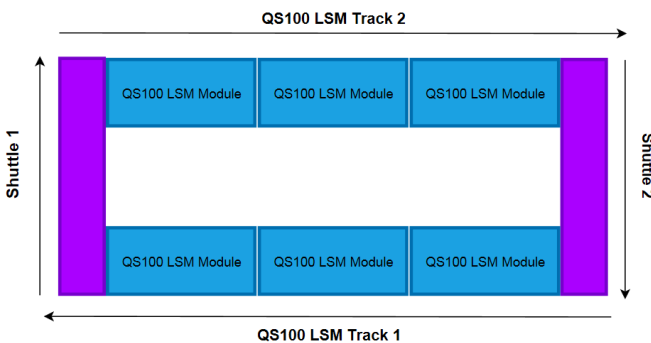


Fig. 7 LSM QS100 Experimental Test-bed Layout

III. EXPERIMENTAL OVERVIEW, RESULTS AND DISCUSSION

A. Experimental Overview

An experimental test-plan was established in which a number of vehicle velocities were selected (0.0135, 0.03, 0.06, 0.2, 0.4, 0.5, 1.0, 1.5 m/s) based on the requirements of the process application under study. Each velocity was measured employing the CPS wireless platform and for each experiment magnetic data was recorded in real-time and transmitted wirelessly to a central server repository for further analysis.

A single measurement comprised a full traverse of 3 straight-line modules of the QS 100 LSM transport system test-bed. The experiments were repeated for each investigated LSM vehicle velocity. A sampling frequency of 150 Hz was selected for the experiments on the basis of the expected motor cogging frequency information (0-30 Hz) provided by the manufacturer of the LSM system [7]. The hypothesis is that motor cogging frequency should in practice map closely to the magnetic field frequency emitted by the LSM under study which in turn influences the vibration profile of the system [9].

B. Experimental Results and Discussion

1) Time Varying Magnetic Field

Fig. 8 shows the magnetic field measured along the Z axis over one of the QS100 LSM paths with the vehicle travelling at a speed of 0.5 m/s. Given that the vehicle is of 0.3m width, the total distance travelled over the 3x QS100 LSM path is 2.7 meters which the vehicle covers in this particular case in 5.4 seconds. The measured magnetic field shows the presence of a time variant magnetic field with higher peaks in magnitude as the vehicle transitions from a QS100 LSM module to the next one and with secondary peaks in magnitude as the vehicle passes through the middle of the QS100 LSM modules. This pattern of the magnetic field has been consistent through the entire data capture, for every speed of the vehicle studied.

Given that the QS100 LSM module integrates a feedback, control and sensing infrastructure that enables accurate positioning of the vehicle and synchronization of the magnetic fields generated by the individual motors, it is the observation of the authors that the high magnitude magnetic field peaks at the transitions between LSMs is likely as a result of the control loop signals that aim to synchronize the magnetic field generated by each LSM module and the vehicle itself and provide a smooth transition between them.

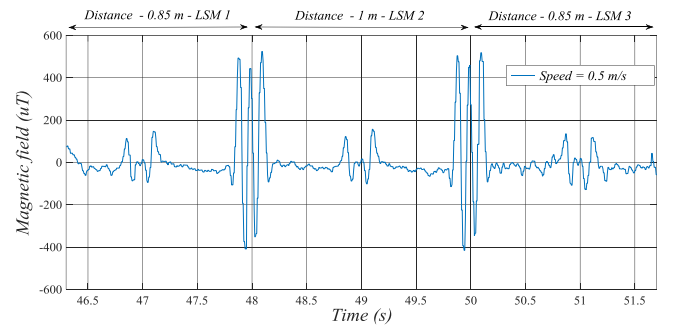


Fig. 8 Magnetic field measured over a 3 meters LSM path with an LSM vehicle speed set to 0.5 m/s

TABLE III. VEHICLE SPEED VS. MAGNETIC FIELD FREQUENCY

Vehicle Speed (m/s)	B_z Frequency (Hz)
0.0135	0.3
0.03	0.6
0.06	1.25
0.2	4
0.4	8
0.5	10
1.0	18.87
1.5	31.25

2) Magnetic Field Magnitude and Frequency:

An analysis of the magnitude of the magnetic field peaks rendered the results comparable for all the vehicle speeds. Magnitudes in the range of ± 800 uT at the transition between QS100 LSM modules and ± 100 uT as the vehicle crosses the middle of each QS100 LSM module were recorded uniformly for all vehicle speeds with a variation of ± 20 uT. An example illustration of the magnitude results is presented in Fig. 8. The range of magnetic field frequencies recorded as part of the experiments for various vehicle speeds are shown in Table III. The frequencies range from 0.3 Hz at a vehicle speed of 0.0135 m/s up to 31.25 Hz at a vehicle speed of 1.5 m/s.

As mentioned previously research in low frequency magnetic field energy harvesting has been demonstrated at frequencies below 100 Hz [14, 15, 18-20]. As an example Brooks coils were employed to harvest energy at a magnetic frequency of 60 Hz and with magnetic field of 21.2 uT. The study reported a demonstrated recoverable power in the order of 6.32 mW [15]. The frequency range in tandem with the magnitude of the magnetic field particularly at module transition and mid module would indicate that the magnetic field profile found as part of this empirical study may be suitable for energy harvesting.

3) Magnetic Field Frequency relation to LSM Vehicle Velocity

Establishing that a relationship exists between magnetic field frequency f_B and LSM vehicle velocity $v_{vehicle}$ should be employed as part of the specification and design and development of any subsequent energy harvesting solution. This information can in turn enable the proposed methodology made to function and generate power at varying vehicle velocities. Fig 9 shows the linear regression between the frequency of the measured magnetic field and the vehicle speed. The linear relationship between the two variables could then be represented by the following:

$$f_B = 20.3295 * v_{vehicle} - 0.1275 \text{ (Hz)} \quad (3)$$

With $v_{vehicle}$ being the speed of the vehicle in m/s. This model results in a coefficient of determination $R^2 = 0.9968$ that indicates how well the model represented by equation (3) can predict the frequency of the magnetic field from the speed of the vehicle. Given that the vehicle speed of the QS100 LSM can vary from 0 to 2.5 m/s, the frequency range of the magnetic field will vary linearly between 0 to 50 Hz. In practice the LSM system under study will spend a significant portion of its operational schedule at speeds of 1 m/s or greater generating a time varying magnetic field with frequency in the order of 20 to 50 Hz.

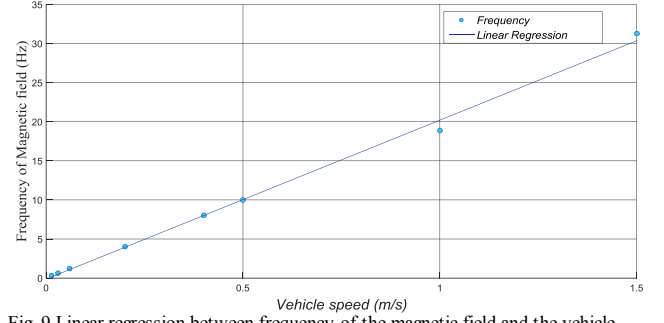


Fig. 9 Linear regression between frequency of the magnetic field and the vehicle speed

4) Non-Cancelling Magnetic Flux:

To reduce the complexity of the energy harvesting implementation it is beneficial to establish that a uniform non-cancelling magnetic flux is present, spanning the magnet array, enabling the use of a single receiving coil in an energy harvesting implementation. Fig. 10 illustrates the magnetic field, measured along the Z axis over one of the QS100 LSM tracks measuring at the 4 sensor deployment regions described in Table II. With the vehicle travelling at a speed of 0.03 m/s over a 3x QS100 LSM module path, the travelled distance of 2.7 meters is traversed in 90 seconds.

As can be validated in Fig. 10, $\frac{dB}{dt}$ exhibits the same polarity for all the regions under study. According to (2) this would indicate that the time variation of the magnetic flux would not introduce terms in the generated voltage that would potentially cancel each other in the practical implementation of an energy harvesting solution. Assuming that the dimensions and direction of the surface area of the receiving coil is kept constant in relation to the magnetic field, the magnet array could potentially be addressed with a single receiving coil reducing the complexity of the practical implementation of an energy recovery system.

IV. CONCLUSIONS AND FUTURE WORK

The goal of this work was to determine the feasibility of harvesting energy directly from an operational LSM transport system employed in high volume manufacturing. An LSM vehicle was instrumented with microelectromechanical (MEMs) based sensor technology, deployed as part of a wireless cyber physical system (CPS), to perform near real-time magnetic field measurement for a mobile LSM vehicle. A series of experiments were designed and conducted to establish the magnetic profile of the system.

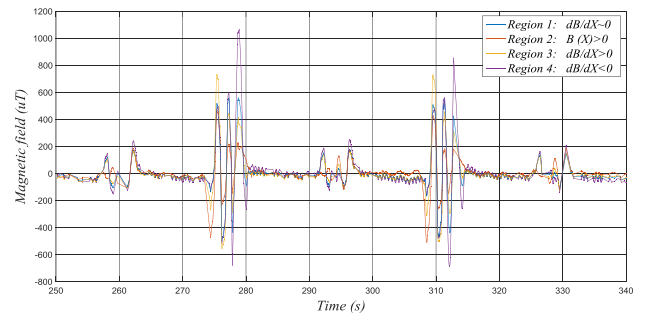


Fig. 10 Magnetic Field measured by sensors at locations indicated in Fig 6. Example provided is recorded with LSM vehicle speed set to 0.03 m/s.

Experimental data capture was conducted on a cycled LSM test-bed comprising of 2 shuttles and 2 x 3 meter lengths of LSM track. Varying vehicle speeds were incorporated in the experimental regime to reflect realistic operational conditions. The recorded magnetic profile was shown to satisfy a number of key criteria for the development of a suitable energy harvesting paradigm.

A time varying magnetic field was demonstrated to exist during LSM vehicle movement, such that an accompanying varying electric field is generated, in which a coil can be orientated to recover energy. The magnetic field magnitude and frequency were measured and the operational frequency range (20 to 50 Hz) in tandem with the magnitude of the magnetic field, particularly at module transition (± 800 uT) and mid module (± 100 uT) would indicate that the magnetic field profile found as part of this empirical study may be suitable for energy harvesting.

A linear relationship between magnetic field frequency and LSM vehicle velocity was established, such that any subsequent proposed energy recovery methodology could be designed to function and generate power at varying vehicle velocities. Finally through the examination of magnetic information recorded at multiple locations on the LSM magnet array a uniform non-cancelling magnetic flux was shown to be present during operation. Working under the assumption that the dimensions and direction of the surface area of a suitably designed receiving coil is kept constant in relation to the magnetic field, the magnet array could be instrumented with a single receiving coil.

Future work will focus on the implementation and optimization of a single energy harvesting coil including magnetic core material and/or a magnetic flux guide and on the power conditioning of the receiving coil signal. An experimental validation of the energy harvesting system will be conducted on the test-bed employed as part of this study.

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