POTENTIAL FOR IMPROVING OPERATIONAL EFFICIENCY OF ROBOTIC SYSTEMS UTILIZING COST EFFECTIVE CORE-LESS WIRELESS CHARGING SYSTEMS

Leslie R. Adrian[1,2], Aivars Rubenis[3]
[1]SIA "Lesla", Latvia; [2]Riga Technical University, Latvia; [3]SIA "TransfoElectric", Latvia
leslie.adrian@rtu.lv, aivars.rubenis@transfoelectric.com

Abstract. Industrial Service Hybrid robots (ISH) are becoming increasingly popular and are finding many applications in both domestic and semi industrial areas. One important example is the use of robots within storage facilities attending to the mundane tasks of product movement, placement and retrieval at both large and small warehouse facilities. Of particular interest is the downtime of the robot when undergoing a recharge cycle. The time consumed during charging varies according to the battery type and this time may be categorized as being both non-productive and inconvenient especially to small storage facilities, where a minimal amount of robots have been purchased to perform the tasks. Therefore, there is a need for total autonomy of the ISHs and the proposed solution is wireless power transfer (WPT) that can render the charging of mobile robots autonomous by removing the requirement for downtime for charging. In this research, a complete WPT charging system has been developed for dynamic recharging of mobile robotic platforms. The system includes primary power conversion, magnetic coupling methodology, transmitter and receiver overview and describes a new low-cost coreless transmitter technology, which is easily installed and more suitable for the smaller business owner, yet also capable of operation in bulk storage locations. The design of this WPT charging system is presented as a fully controlled and dynamic solution for mobile robots. Within the paper, analytical and experimental results are presented.

Keywords: robotics, WPT, resonant, dynamic, charging.

Introduction

The number of autonomous ISH robots [1] within manufacturing, production and warehouse sites is growing at a steady rate. Previously the preferred charging methods applied have been the manual replacement of depleted batteries with recharged batteries or alternatively the mobile platforms are taken offline for the sole purpose of recharging, which is accomplished by an electrical contact point system or, in some instances, connecting to standard connectors by an assistant. Either method detracts from the idea of autonomy and results in downtime for the machine and possible losses in production. Cyclic recharge times therefore should be regarded as a hindrance and avoided where possible.

The authors' response is to initiate a fully dynamic Wireless Power Transfer (WPT) system, capable of maintaining a constant full charge to the mobile robot fleet, irrespective of the size and in this respect a fully functional system suitable to this task has been designed. The primary author has been investigating WPT systems for many years and is of the opinion, that air core technologies offer the widest solutions within the field. Transformer based WPT systems are both costly, excessively heavy and do not lend themselves well to filling the gap between wired and non-wired near field transmission. More and more examples of technologies utilizing air or hollow core Tx and Rx systems are being examined with promising results [2; 3].

A near field magnetically coupled resonating system is used [4], comprising multiple transmitters along an array of conveyor pathways aligned and designed in accordance with the mobile robots' required work path. Essentially the robots are AAGVs (Autonomous Automated Guided Vehicles) and therefore certain system parameters were set according to logical requirement.

- The WPT conveyor pathway is in an "always off" mode (refer Section 1).
- The system output be constrained to < 0.5 kW in accordance with common AGV requirements (Refer Section 2a).
- Electromagnetic interference should be minimal and in line with current regulation (Refer Section 2).
- Battery systems should be super capacitor boost assisted, utilizing the design of a newly developed electronic load system (briefly covered in this paper).
- The system be cost effective and operationally efficient.

Section 1: Methodology – conveyor pathway

The conveyor pathway or Tx track consists of multiple transmitter coils paralleled as a pathway designed to suit the floor plan of the user and is able to be configured in many variations, Fig. 1. The construction of the conveyor track is durable and manufactured in sectional lengths, made of water resistant polymerized rubber, which is both low in profile (approximately 4mm) and electrically inert. The pathway may be fixed in situ or laid, allowing ease of installation. The transmitter coil manufacturing processes are not the subject of this paper. The conveyor pathway has been designed in an "always off" mode, which is preferable from both the electromagnetic emissions and efficiency perspective. Embedded analog components within the robot chassis and the Tx coils activate the WPT processes individually on each coil as the ISH traverses its course.

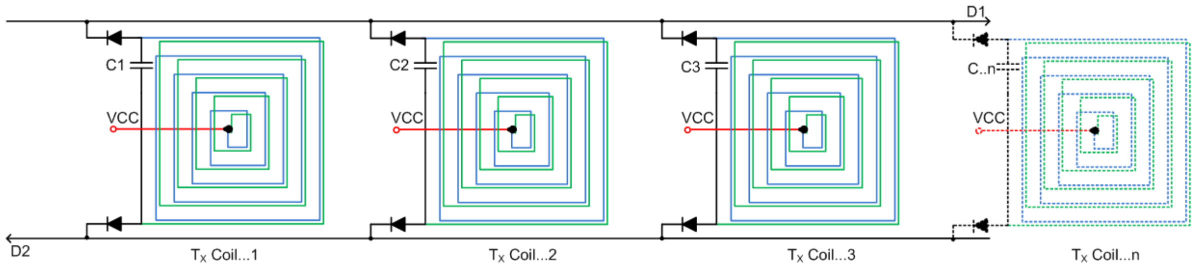

Fig. 1. **Conveyor pathway:** simplified schema

In order to obtain power transfer only to the Tx coil, at which the robot is present, the authors have investigated other methods such as the use of a resonant or even-mode frequency of double-peak feature for power transfer, which theoretically induces the magnetically resonant transmitter coil into a low impedance state [3]. Although the method somewhat reduces electromagnetic radiation, the addition of multiple inductors (L) and multiples of oscillation capacitors (C) in a parallel configuration, simultaneously increases parasitics and reduces overall efficiency as the coils are in a constant "oscillation" state, even though they are not resonantly active with the receiver coil as can be seen in Fig. 2 from [3].

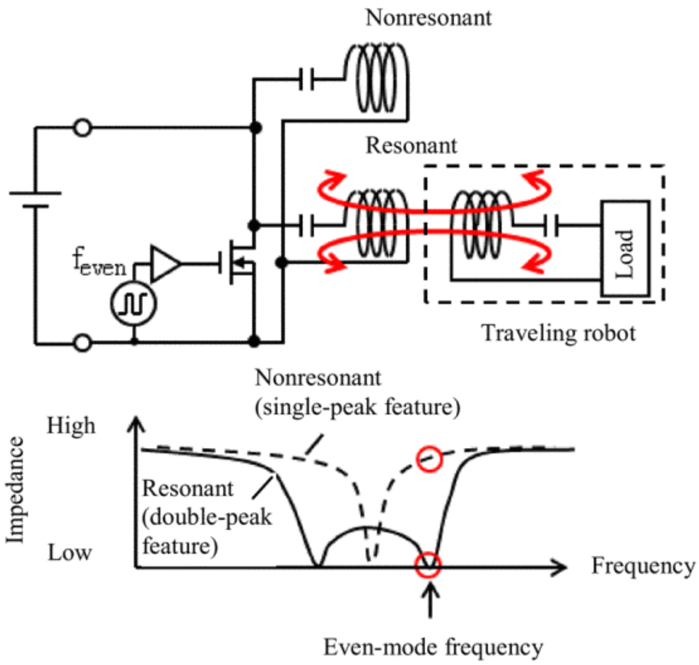

Fig. 2. **Power feed system:** incorporating two transmitter coils from [3]

In Fig. 2 the addition of multiple non-resonant transmission coils as a parallel array within this scheme may create an unstable system, although with a two coil only system, as shown, would not be noticeable and in fact the authors [3], have described only a two part system in their conclusions. Therefore, the authors preferred the method to utilise a primarily analog system, which consists of a switching mechanism embedded in the conveyor pathway and a MCU Controller system on the ISH chassis. The simplified schematic, as shown in Fig. 3, provides continuity of charge as the robot traverses the conveyor path as each of the IR emitters cross over the inline phototransistors. The arrays of emitters and phototransistors are fully tuned and therefore not subject to ambient influence. At any moment there is ignition of two Tx coils due to the configuration of switching arrays, so that as the robot passes from one coil to the next, the preceding coil will continue to propagate energy to the next coil, as is the case with intermediate resonant coils, and according to the temporal coupled mode theory (CMT), the intermediate system power transfer efficiency has been shown to be improved considerably in the cases of not only a coaxially arranged intermediate system, but also a perpendicularly arranged intermediate system [2]. Together this institutes a form of energy "soft-start", which is beneficial to long term battery charging configurations. Together the emitter and photo array serve a dual purpose. When the ISH battery and super capacitor bank are at full charge, the receiver's resistive load (through certain modification) becomes large, which serves to increase the impedance, therefore restricting the current to be able to pass to the receiver, in effect, converting from a time to a trickle charge receiver.

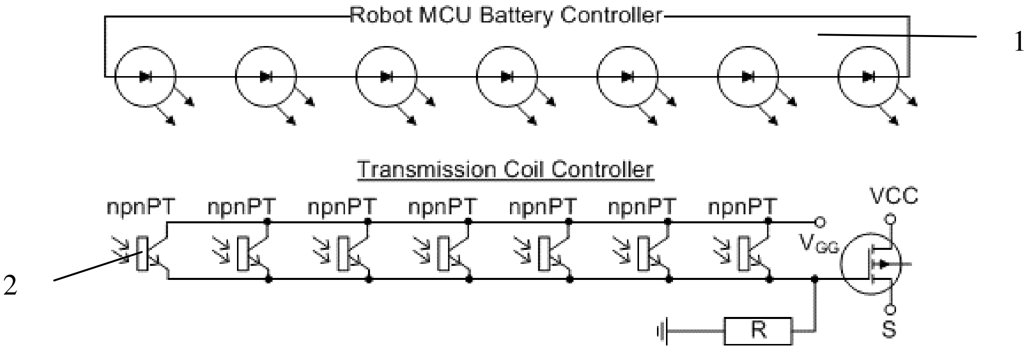

Fig. 3. **Tx switch controller:** 1 – Rx chassis IR array; 2 – Tx embedded pathway array

Section 2: Methodology – ISH Chassis

The lower chassis of the ISH is the section referred to as the mobility part or mobile platform, which herein will be discussed further. The upper portion of the ISH is able to be configured as per user requirement and is related to the moving, lifting, placement and retrieval of items as packages, tools or the like. The structure, for example, may be a simple storage rack to carry goods to a specific location, with the packing and unpacking performed by an attendant or the ISH may be totally autonomous with a fork lift type arrangement for product or item placement, however, the methodology and construction of this part does not form a part of this paper.

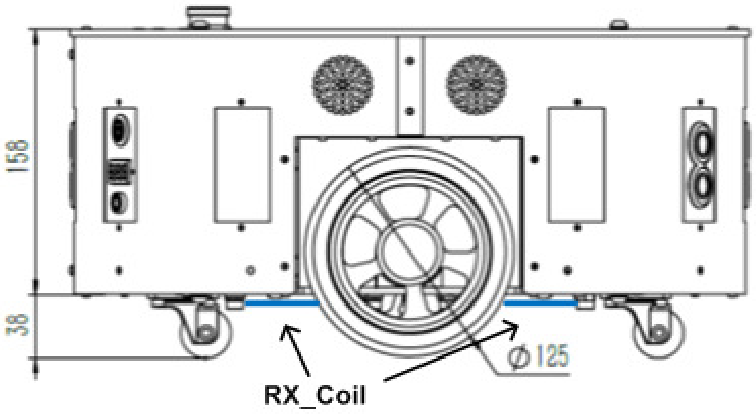

Fig. 4. **ISH robot chassis:** fully shielded robot drive base

The ISH chassis as seen in Fig. 4 is a fully self contained unit. Quick specifications may be found within Table 1. The primary purpose of the ISH chassis is as a fully programmable, mobile load carrier. The Rx coil for the WPT process is embedded in the lower base of the ISH and is equal in diameter to the radius of the chassis, but may be adjusted for varying power needs. Internal chassis walls are lined with nickel-copper adhesive sheet to further shield against unwanted EMI. In the near future a full radiation analysis will be performed on a fully operational conveyor track and will become the subject of further publications. Due to the size considerations placed, when creating the transmitter, receiver and ISH, the ISH of itself becomes the EMI shield as it traverses the conveyor pathway. Having an inductive/resonant WPT system the unit operates in a very "near field" environment, which lends itself to self regulated shielding.

Table 1

ISH Chassis - Specifications

Item	Comments
Size, mm	Φ450 x 250
Ground clearance, mm	34mm
Rx Coil, mm	220 to 350mm OD
Drive Wheels	2 x 125mm OD
Stabilizer Wheels	2 x Castor
Drive Mode	2 Wheel Differential Drive
Load	≤ 60 kg
Maximum Speed	$0.85\ m\cdot s^{-1}$
Battery Capacity (1)	12V 14000mAh
Battery Capacity (2)	24V 28000mAh
Ultra-Capacitor Rx Electronic Load	16.2V 80 F

Section 2a: Methodology – Wireless Power Transfer System

The system is currently constrained at < 0.5kW with this version able to extend to 1kW, if required. The remedial circuit denoted in Fig. 5 represents the system, based on the "Royer" push pull oscillator/power converter. The Tx switch controller from Fig. 3 is a two part system, in which the robot side, with the assistance of the MCU controls various functions relating to the Rx coil and the sensor array on the Tx side simply controls "on-off" operation of the Tx coils.

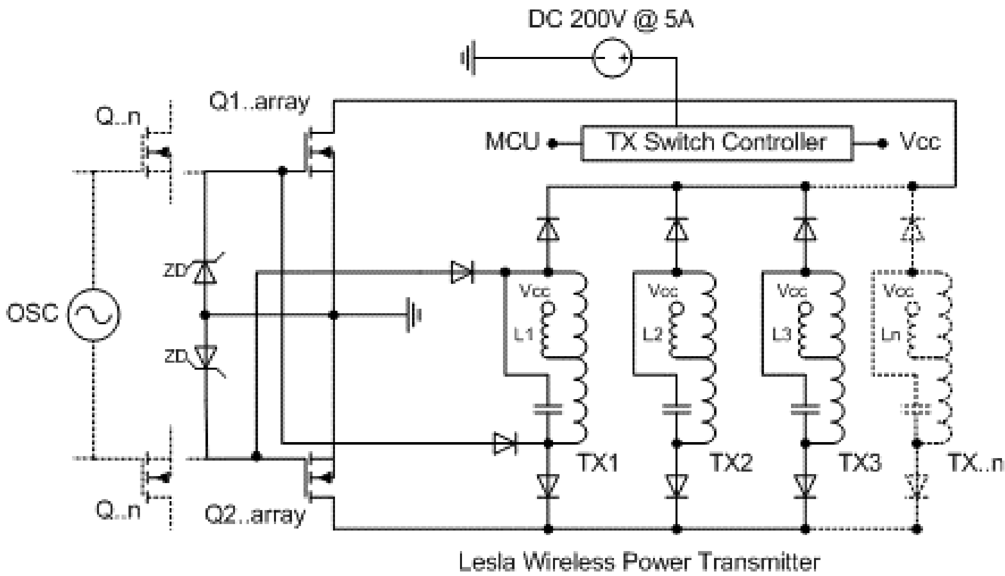

Fig. 5. **WP transmitter:** simplified schema

The configuration of the simplified inductive resonant WPT system may be seen in Fig. 7. K_1, K_2 and K_{12} are the Tx to Rx coupling coefficients. The resonant coils are identical in design from a resonance perspective and placed in a very near field configuration with axis alignment. Transmission distance does not exceed 50mm in this application. With application of CMT, the Tx, Rx system may be represented as in (1).

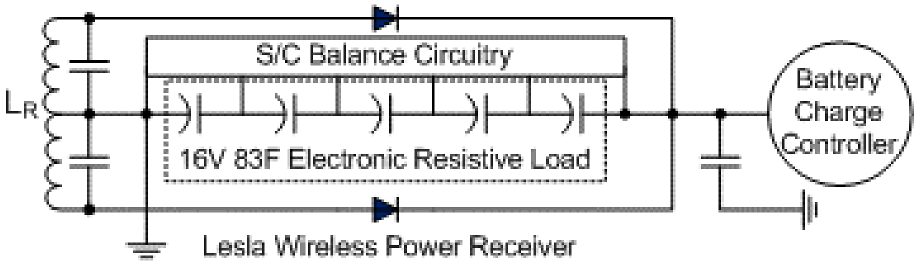

Fig. 6. **WP teceiver:** simplified schema

$$\begin{pmatrix} \dot{\alpha}_1 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} -\left(j\omega_1 + d_1\right) & jK_{12} \\ jK_{21} & -\left(j\omega_2 + d_2 + xd_2\right) \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix}, \tag{1}$$

where a_i – common mode amplitude of Tx and Rx;
k – coupling coefficient Tx to Rx;
x – virtual or relative decay rate, Rx as a load;
d_i – natural decay rate of resonance;
ω_i – $\text{freq}_{\text{angular}}$ of Tx and Rx as a resonant system.
i – Tx(1) & Rx(2).

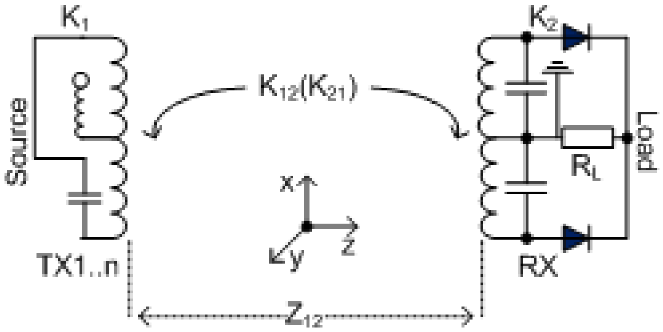

Fig. 7. **WPT system:** simplified CMT configuration

The mutual inductance between two resonant tuned coils of almost identical geometry becomes a function of the distance separating the coils (2). Therefore, we look to find the most beneficial mutuality (3) between Tx and Rx, which, in an ideal system, would be as in the series or parallel equations denoted in (4), creating a system, where mutual impedance and mutual resistance may be minimal.

$$Z_{12} = j\omega M + R_{12}, \tag{2}$$

where Z_{12} – mutual impedance between Tx and Rx;
M – mutual inductance between Tx to Rx;
R_{12} – mutual resistance between Tx to Rx.

$$Z_{12} \approx R_{12} \approx 0, \tag{3}$$

$$k = \frac{K_{12}}{\sqrt{x_1 x_2}} \approx 0.8 \text{ or } k = \frac{J_{12}}{\sqrt{b_1 b_2}} \approx 0.8, \tag{4}$$

where K_{12} – impedance-inverter parameters;
J_{12} – admittance-inverter parameters;
$x_1 x_2$ – reactance slope parameters;
$b_1 b_2$ – susceptance slope parameters.

The modelling indications were made on the basis of the almost identical nature of the Tx and Rx coils and within those calculations it was found that Z_{12} was sufficiently small, (38mm) with $K_{12} \approx 0$ and $k > 0.8$ (estimated coefficient). The modelled results versus the bench test analysis are shown in Fig. 8. Stable efficiency becomes apparent at an average of 93 % from the 0.25 kW mark to the 0.5 kW mark with some variations apparent due to the soft start configuration of the inverter.

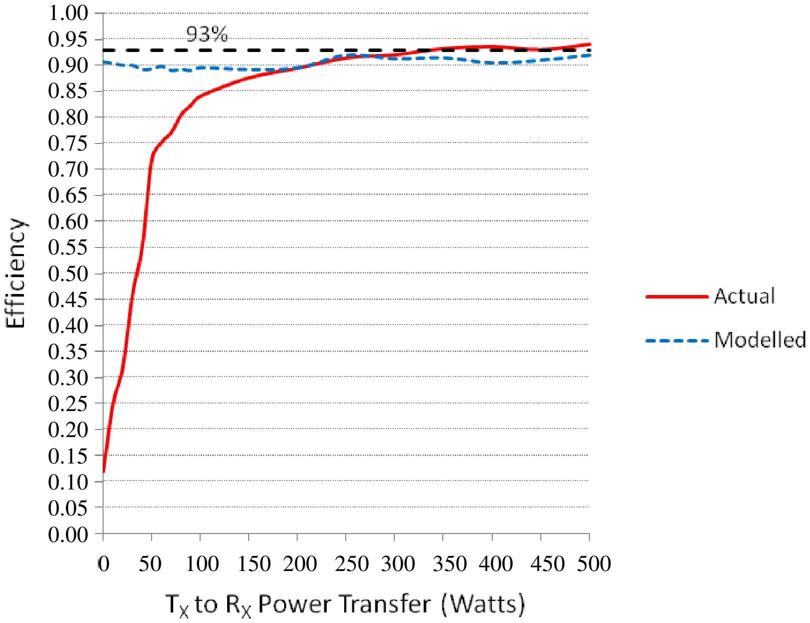

Fig. 8. **Transfer characteristics:** efficiency bench test

Conclusions

Designed to operate as a 1 kW system, the bench test provided encouraging results, and for the purpose of experimentation, represented a system capable of dynamic charging of multiple mobile robot platforms on a conveyor pathway. The requirement was to establish a high efficiency 0.5 kW model. This has been accomplished along with 93 % efficiency transfer. (Gate losses of the inverter have been excluded from the study, however, will be fully analysed in further studies). The theoretical calculations are in agreement with the measured results, except for that part in Fig. 8, where no allowance for soft-start of the inverter was included. Therefore, from the 0 to 200 Watts mark there is a distinct error. Additionally, from 50 Watts through 200 Watts there is a noticeable decrease in the resulting transfer efficiency, which warrants further investigation. At present, the system appears to operate best from 50 Watts to its limit of 1 kW. When installed, the system will be fully analyzed to further increase the efficiency, reduce EMI emissions and refine the production methodology.

Acknowledgements

This paper has been published within the research project "Research on development of wireless charging and control system for industrial service robots" within grant program by European Regional Development Fund for general industrial research and for projects dealing with new product and technology developments. Central Finance and Contracting Agency of the Republic of Latvia contract number 1.2.1.1/16/A/003.

References

[1] Adrian L.R., Ribickis L. Proposed Piezoelectric Energy Harvesting in Mobile Robotic Devices. Power and Electrical Engineering of Riga Technical University (RTUCON), 2014 55th International Scientific Conference on , vol., no. 14, 14 Oct. 2014, pp.63-66.

[2] Kim J., Son H. C., Kim K. H., Park Y. J. Efficiency Analysis of Magnetic Resonance Wireless Power Transfer With Intermediate Resonant Coil. In IEEE Antennas and Wireless Propagation Letters, vol. 10, 2011, pp. 389-392.

[3] Sugino M., Kondo H., Takeda S. Linear motion type transfer robot using the wireless power transfer system. 2016 International Symposium on Antennas and Propagation (ISAP), Okinawa, 2016, pp. 508-509.
[4] Sample A. P., Meyer D. T., Smith J. R. Analysis, Experimental Results, and Range Adaptation of Magnetically Coupled Resonators for Wireless Power Transfer. in IEEE Transactions on Industrial Electronics, vol. 58, no. 2, Feb. 2011, pp. 544-554.