Wireless Power and Communication Transmission for Industrial Robots

Matjaz Rozman, Khaled M. Rabie, Bamidele Adebisi,
School of Engineering, Division of Electrical Engineering
Manchester Metropolitan University, M1 5GD UK
Emails:matjaz.rozman@stu.mmu.ac.uk; {b.adebisi, k.rabie}@mmu.ac.uk

Abstract—**Mid-range resonant wireless power transfer (WPT) gained tremendous attention due to the higher efficiency. However, the relatively narrow transmission band has been simply drawn the technology back from being implemented in an application where the data and a power transmission are required. In this paper both the simulation and a practical implementation of a Strongly Coupled Magnetic Resonant (SCMR) system with a high frequency band for simultaneous data and power transmission is proposed. With this method communication and a power transmission can be transmitted in an industrial robot applications. Multiple T_X and a single R_X loop are placed between the joint of the robot in order to increase frequency spectre. The simulation has been developed in the theoretical analysis of equivalent circuits of the improved SCMR system. The analysis eventually leads to the factual parameters of a WPT system to provide its maximum efficiency for both wireless power and data transmission for an industrial robot. Besides the analysis has been validated with a comparison between the simulation results and practical implementation.**

I. INTRODUCTION

Until 1921 "robot" was just a term limited to science fictions. Furthermore, fictions were turned into a reality by an English researcher William Grey Walter, creating the world's first autonomous robot with a complex behaviour in the late 1940s. With today's thriying technology, variety of robots such as droids, drones and robots are widely available for multiple purposes [1]. The introduction of the industrial robots replacing human work force, has resulted fivefold reduction in the defect rate, consistency, increased production and quality. Thus the robots are used to perform heavy duty, hazardous and repetitive work which is preferably not carried out by humans. According to IEEE.Org, it is also expected that by the end of 2018, China will have over 400,000 industrial robots, surpassing North America and the European Union in the number of robots operating in factories.

Three most widely utilised robot configurations for industrial automation can be listed as articulated robots, selective compliance assembly robot arm (SCARA) robots and gantry robots. Robots anatomy consists of joints and links to aid positioning and orientating, relatively accomplished by the inner (primal) joints and outer (distal) joints [2, 3]. However, the motion of an industrial robot is constrained by joint limits such as working angle due to the surrounded wires or the power supplying cables, as shown in Fig. 1A. An increment of the working angle of the robot as shown in Fig. 1B, will improve the speed and reduce the power consumption of the robot. The robot will no longer be limited by the working angle, moreover will be able to use the shortest distance towards the next move.
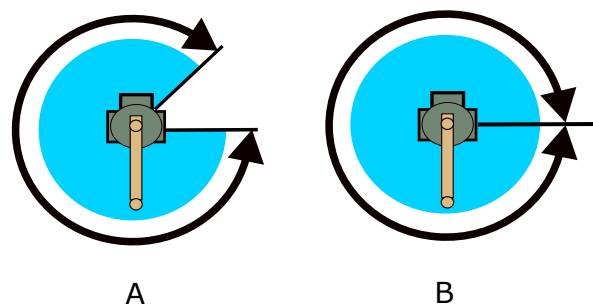

Fig. 1. Top view of (A) the work envelope of a typical SCARA horizontally articulated robot configuration and a robot configuration with SCMR technology (B)

Wireless Power Transfer (WPT) is another widely researched topic, which has been growing leaps and bounds in the last few years due to a sudden escalated awareness of wireless charging with the flourishing number of portable electronic components. By using WPT, all electronic devices will be capable of charging themselves, eliminating the conventional batteries or being plugged, which is hazardous, inconvenient and also simultaneously costly. Nicola Tesla became the first scientist to convince the WPT concept over his experiments, duplication of the work of Heinrich Hertz to power vacuum bulbs wirelessly in the early 20th century [4]. Nevertheless the experiment was not continued further due to the identified hazards, which were more likely to affect both the environment and the human factor.

A conventional SCMR system consists of two separate loops at close proximity [5, 6]. In order to increase the transmission distance of the WPT system, both the transmitter and receiver loops must have the same oscillating frequency [7, 8]. A maximum transmitting efficiency of the system can be achieved at the same frequency as the oscillating frequency of the loops. Numerous attempts have been made to enhance the frequency spectrum of the SCMR WPT system [9, 10]. For instance, the researchers in [11] have victoriously increased a frequency spectrum of comformal strongly resonant (CSCMR) WPT system.
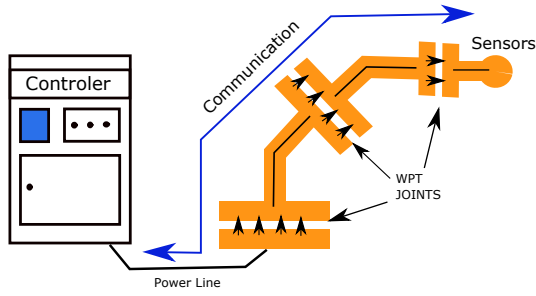
Fig. 2. Power and communication between the controller, robot and the sensor.

Fig. 3. Schematic model of the proposed SCMR system which enhances the frequency spectrum of the WPT for data transmission

However, this paper focuses on the SCMR method, which is competent in transferring both power and data with high efficiency within short range, hence it is a more satisfactory solution to be implemented in robotic applications. In contrast with power transfer using slip ring, SCMR methor does not require friction between the two coils, thus does not induce noise into transmission channel [12, 13]. The frequency spectrum has been increased by connecting multiple coils in parallel with each other. Proposed method also reduces the complexity of the T_X circuit, where only one resonant capacitor is used to tune the transmitter. Moreover, all the individual inductances in the transmitter coil are equivalent, but vary in size. This effort meant to enhance the flexibility of the industrial robots in many aspects, once implemented the degree of freedom angle will no longer be a crucial factor as presented in Fig. 2. The robot will be able move faster, thus will escalate the productivity while minimising the energy costs.

Initially, in section II a mathematical analysis of the proposed circuit has been illustrated. In section III practical implementation of the loops, is described. The results are explained in section IV, both the conclusion and the future work have been discussed in section V.

II. CIRCUIT ANALYSIS OF SCMR SYSTEM

The electromagnetic resonance WPT concept is typically formed by two resonance coils: a transmitting resonator (T_X) and a receiving resonator (R_X), which resonate at the same frequency where their quality factor (Q) is maximised. In a robot application, the coils may have the same diameter, which will simultaneously increase the transmission distance. Fig. 3 indicates the schematic of the proposed SCMR system with a multiple transmitter loop, embedded into the same plane. R_X is represented by a single loop resonator while the distance between the two is represented by a coupling factor (k), between them.
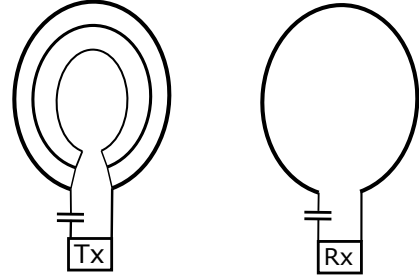
Schematic diagram, Fig. 3 has been modelled into an equivalent circuit model as shown in Fig. 4, in order to represent how the proposed multi-loop SCMR system functions. T_X side is represented by five independent inductance coils. Inductor ZL_1 together with the oscillating capacitor ZC_1, forms a power transmission loop. Inductors ZL_2, ZL_3, ZL_4 and ZL_5 are parallel connected set of inductors which are connected together with the capacitor ZC_2 in order to form the data transmission part of the WPT. This set of inductors, together forms a T_X loop, in which every loop is connected to R_X resonator by the coupling factor k. The R_X loop is represented by an inductor ZL_6 and an oscillating capacitor ZC_3.
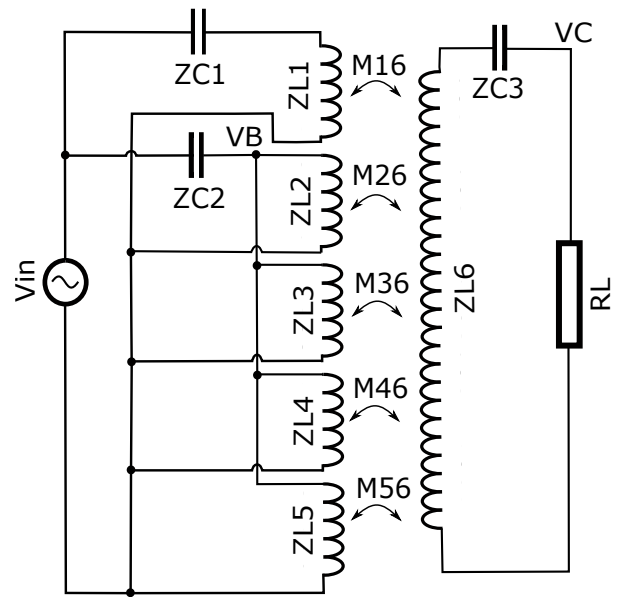

Fig. 4. Equivalent circuit of the CSCMR system with one pair of resonators

By applying Ampere's and Faraday's electromagnetic induction law, the magnetic induction field H, from one of the two parallel coaxial loops at d, distance can be expressed as [14]

$$H_y = \int \triangle H_y = \frac{I_X r_y^2}{2(r_y^2 + d^2)^{\frac{3}{2}}} \quad (1)$$

The mutual inductance of the two loops can be derived by including the area enclosed by the coil and can be written as

$$M_{xy} = \frac{\psi_{xy}}{I_y} = \frac{B_y A_x}{I_y} = \frac{\mu_0 \pi r_y^2 r_x^2}{2\sqrt{(r_y^2 + d^2)^3}} \qquad (2)$$

The angular frequency of the LC circuit can be calculated as $\omega = \frac{1}{\sqrt{LC}}$. However, in the proposed circuit the angular frequency can be calculated by taking into account each inductor connected in series as

$$\omega = \frac{1}{\sqrt{(L_1 + L_2 + ... + L_N)C}} \qquad (3)$$

The circuit diagram in Fig. 4 can be solved by applying Kirchhoff's Voltage law (KVL) to the SCMR system. The currents ($I_1 \sim I_6$) in the circuit can be calculated as follows

$$I_1 = \frac{(V_{in} - j\omega M_{16} I_6)}{(j\omega ZL_1(\frac{1}{j\omega C1}))}$$

$$I_2 = \frac{(V_{in} - j\omega M_{26} I_6)}{j\omega ZL2(\frac{1}{j\omega C_2})}$$

$$I_3 = \frac{(V_{in} - j\omega M_{36} I_6))}{j\omega ZL_3}$$

$$I_4 = \frac{(V_{in} - j\omega M_{46} I_6)}{j\omega ZL_4}$$

$$I_5 = \frac{(V_B - j\omega M_{56} I_6)}{j\omega ZL_5}$$

$$I_6 = -\frac{V_C + A}{j\omega ZL_6 \frac{1}{j\omega C_6}} \qquad (4)$$

Where $A = (I_5 j\omega M_{56}) + (I_4 j\omega M_{46}) + (I_3 j\omega M_{36}) + (I_2 j\omega M_{26}) + (I_1 j\omega M_{16})$ and M_x is the mutual inductance between the ith and jth loop. Considering voltages on separate branches a gain on the output can be calculated as:

$$(G) = V_C((B-D)*(jw)^2 + (E-F)jw + G + H) + R_L(B) \qquad (5)$$

where

$$A = ((J+K)V_{in}(jw) + NV_{in} + (O+P)V_B))$$
$$B = -ZC_2 ZC_6 ZL_1 ZL_3 ZL_4 ZL_5 M_{26}^2$$
$$D = ZC_1 ZC_6 ZL_2 ZL_3 ZL_4 ZL_5 M_{16}^2$$
$$E = -ZC_6 ZL_1 ZL_2 ZL_3 ZL_4 M_{56}^2$$
$$F = ZC_6 ZL_1 ZL_2 ZL_3 ZL_5 M_{46}^2$$
$$G = ZC_6 ZL_1 ZL_2 ZL_3 ZL_4 ZL_5 R_L$$
$$H = ZL_1 ZL_2 ZL_3 ZL_4 ZL_5 ZL_6$$
$$J = -ZC_2 ZC_6 ZL_1 ZL_3 ZL_4 ZL_5 M_{26}^2$$
$$K = ZC_1 ZC_6 ZL_2 ZL_3 ZL_4 ZL_5 M_{16}^2$$
$$N = -ZC_6 ZL_1 ZL_2 ZL_3 ZL_5 M_{46}$$
$$O = ZC_6 ZL_1 ZL_2 ZL_3 ZL_4 M_{56}$$
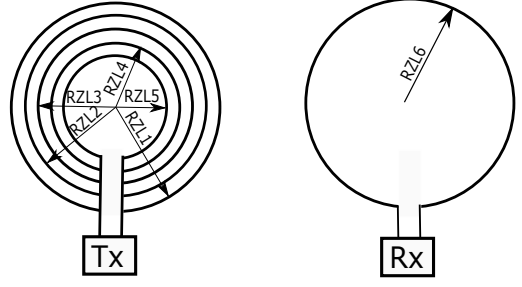$$P = ZC_6 ZL_1 ZL_2 ZL_4 ZL_5 M_{36} \qquad (6)$$

Fig. 5. Transmitter loops and receiver loop diameters

III. CIRCUIT ANALYSIS

The resonant loops have been designed as a circle shape since the robot joints make circular motions where the oval shaped coils provides maximum alignment at any position of the robot arm. T_X coils have been placed concentrically inside same plane to minimize its size. The diameter of the loops varies according to the calculated coupling factor between the T_X and R_X loops. Thus the circuit is designed to demonstrate high efficiency at coupling factor between power transmitter loop and a receiver at 0.5. The rest of the coils are arranged in the way that their coupling factor with Tx coils decreased to 0.1. The circuit has its maximum power transmission efficiency at the frequency of 1.02MHz, where the efficiency reaches 97.8%.

The cross section radius of the resonant loops, as presented in Fig. 5, can be analytically calculated, applying to the equation (2) however, it can be adjusted according to the robot size. The cross section of the power transmission loops for this experiment, can be calculated as 10.2cm while data transmission loops cross section warius from 2.1cm to 9.4cm, depends on the k factor required. Similarly the capacitance required for the loop oscillator can be calculated using (3). Similar to ZC_1, ZC_2 is calculated as 680pF. The radius of T_X loop can be calculated using (3) which is equal to 10.2mm. Based on the calculations, the frequency spectrum of the transmitter increase by adding additional inductors into the circuit. As represented in Fig. 6 a frequency spectrum of the system with single transmitting loop is very narrow. When an additional inductor is added the frequency spectrum increases, and the efficiency is higher than 50% for frequency band from 1MHz to 5MHz. With a third coil added, the frequency band increases further, the efficiency, higher than 50% is reached for a spectrum from 1.3MHz to 8MHz, while maximum efficiency of 92% is reached at frequency of 1MHz.
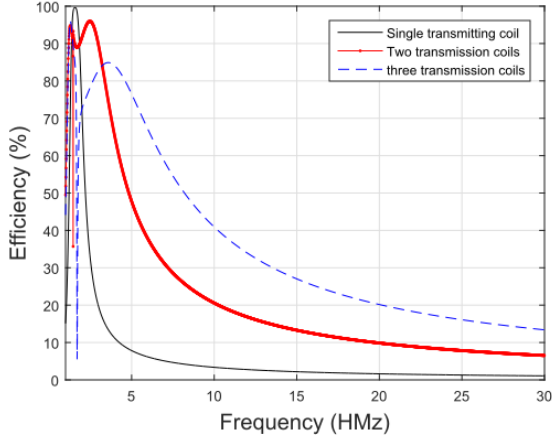
Fig. 6. Comparison of the frequency range between the circuit with two transmitting coils and circuit with three transmitting coils.

Fig. 7 represents the calculated results for a system with a single transmitting loop and a proposed multiple transmitter loop. The analysis illustrates the maximum efficiency of the single loop is for 2% higher that the one with multiple loops with 98%. The frequency spectrum of the system with multiple loops is higher than 50% for a frequency from 200kHz to 1.6MHz and 2.3MHz up to 16MHz. The circuit is able to transmit power with the efficiency of 97, and transmit the data with efficiency as high as 68%. Enhanced frequency spectrum allows the sensors embedded in the robot, to communicate and send the relative crucial information for its functionality.
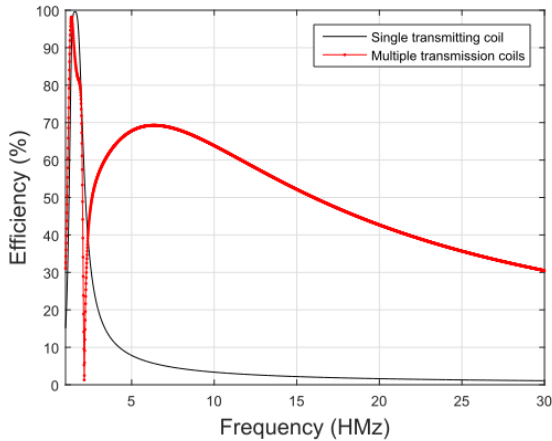

Fig. 7. Comparison between the system with single transmitter coil and the proposed transmitter with multiple coils.

In Table II calculated Transmitter and Receiver loop components are presented.

TABLE I
CALCULATED ELEMENTS

Transmitter	Receiver
$ZC1$, $ZC3=680pF$	$CR_X=650pF$
LT_X1, LT_X2, LT_X3, LT_X4 and $LT_X5=16.37\mu H$	$LR_X=19.65\mu H$

(a) Transmitter coil structure design contains a multiple coils in same plane.

(b) Transmitter and receiver coil as used in measurement set-up.

Fig. 8. Milti-coil transitter used in thos experiment (a) and measurement set up (b).

IV. RESULTS

In this section a result of the practical implementation is compared to the calculated model. In Fig. 8A a practical implementation of a Transmitter loops can be seen. The model contains five loops which are embedded into same plane, however the distance between them varies depending on calculated k required. The coils have been placed inside a plastic housing, in order to secure the position. In Fig. 8B the measurements set-up can be seen. A T_X coil is placed close to the R_X coil. The power is send between the two coils and a effiency of the transmission between them is measured. A signal generator was used to provide power to the T_X, while the results were measured by usb based spectrum analyser.
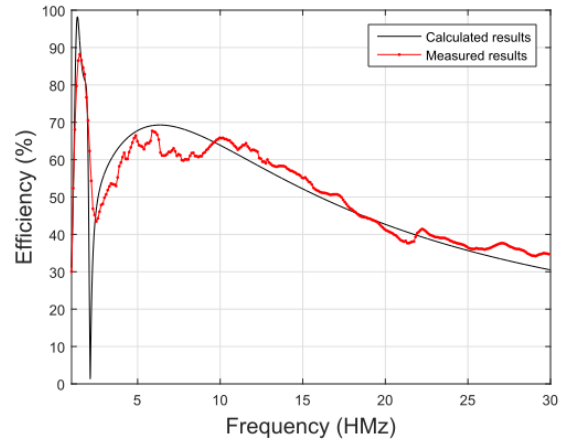

Fig. 9. measurements

The results of the measurements are presented and compared to the calculated values in Fig. 9. It can be seen that the measured curve follows the calculated values, however the measured power transmission efficiency is with 87 for 11% bellow calculated value. A data transmission side reaches 50 efficiency at a frequency of 2.5MHz and falls below that value at 17.6MHz, which form a 15.1MHz frequency band. The measured frequency spectrum is 1.3MHz above calculated value. Overall measured results confirm that the proposed model is able to increase the frequency band of the SCMR WPT system to enable simultaneously power and data transmission.

V. Conclusions

This paper represents an approach of applying the SMRC in robotic applications, where the distance between the transmitter and the receiver stays constant. The system has been designed to transmit both power and data from the transmitter side to the receiver. A mathematical model has been developed to calculate the theoretical efficiency of the transmission based on the coupling factor between milti-coil transmitter and single receiver coil. Calculated results are compared with prototype model. Replacing a conventional power supply for an SCMR based wireless power supply will not only increases the degree of freedom, but also the flexibility to control the robot manipulator from a distant location. Results show that the frequency spectrum of SCMR increase from 2 to 17.1MHz, enabling high efficiency power transmission and create a 15.1MHz communication channel. Efficiency of data transmission varies from maximum 50 to minimum 69%.

Future work will be to extend the distance between the transmitter and receiver while increasing the frequency bandwidth of the signal for higher transmission speed of data. However the SCMR based WPT along with PLC based robot applications could be further customized to suit the industry needs via Industry 4.0.

Acknowlegment

References

[1] M. A. Kamel, X. Yu, and Y. Zhang, "Fault-tolerant cooperative control design of multiple wheeled mobile robots," *IEEE Trans. on Control Syst. Tech.*, vol. 26, no. 2, pp. 756–764, March 2018.

[2] M. Garduño-Aparicio, J. Rodríguez-Reséndiz, G. Macias-Bobadilla, and S. Thenozhi, "A multidisciplinary industrial robot approach for teaching mechatronics-related courses," *IEEE Trans. on Education*, vol. 61, no. 1, pp. 55–62, Feb 2018.

[3] P. Neto, J. N. Pires, and A. P. Moreira, "Accelerometer-based control of an industrial robotic arm," in *18th IEEE Internat. Symp on Robot and Human Interactive Commun., Toyama, Japan*, Sept 2009, pp. 1192–1197.

[4] Y. Wang and W. Chen, "A novel design method of rf lens for long-range wireless power transmission," *IEEE Antennas and Wireless Propag. Letters*, vol. 16, pp. 3159–3162, 2017.

[5] D. Liu and S. V. Georgakopoulos, "Misalignment study of cylindrical scmr wireless power transfer system," in *2016 IEEE Internat. Symp. on Antennas and Propag. (APSURSI), Fajardo, Puerto Rico*, June 2016, pp. 413–414.

[6] Z. N. Low, R. A. Chinga, R. Tseng, and J. Lin, "Design and test of a high-power high-efficiency loosely coupled planar wireless power transfer system," *IEEE Trans. on Industrial Electronics*, vol. 56, no. 5, pp. 1801–1812, May 2009.

[7] Y. Bonan, K. Bao, C. Flores, K. Baza, and S. V. Georgakopoulos, "Efficiency analysis of a conformal scmr system for wearable devices," in *2017 IEEE Internat. Symp. on Antennas and Propag. USNC/URSI Nat.l Radio Science Meeting, San Diego, CA, USA*, July 2017, pp. 1233–1234.

[8] I. Ghotbi, M. Najjarzadegan, H. Sarfaraz, S. J. Ashtiani, and O. Shoaei, "Enhanced power-delivered-to-load through planar multiple-harmonic wireless power transmission," *IEEE Trans. Circuits and Syst. II: Express Briefs*, vol. PP, no. 99, pp. 1–1, 2018.

[9] Y. Wang, Y. Yao, Y. Guan, X. Liu, M. Liu, and D. Xu, "A novel modulation and demodulation method for wireless power and data transmission," in *2017 IEEE Transportation Electrification Conf. and Expo, Asia-Pacific (ITEC Asia-Pacific), Harbin, China*, Aug 2017, pp. 1–6.

[10] W. Xu, T. Cheng, C. Wu, N. Lu, Z. Yang, Y. Lian, and G. Wang, "Ultrathin flexible coils for wireless power and data link in biomedical sensors," in *2017 IEEE 12th Internat. Conf. on ASIC (ASICON), Guiyang, China*, Oct 2017, pp. 604–607.

[11] H. Hu and S. V. Georgakopoulos, "Multiband and broadband wireless power transfer systems using the conformal strongly coupled magnetic resonance method," *IEEE Trans. on Ind. Electr.*, vol. 64, no. 5, pp. 3595–3607, May 2017.

[12] G. He, Q. Chen, X. Chen, and P. Xin, "An accurate modeling method for electric parameters prediction of contactless slip ring," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct 2017, pp. 2051–2056.

[13] J. Zhang, X. Ma, B. Cheng, and Y. Zhao, "Storage life modeling and analysis for contacting slip ring based on physics of failure," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 7, no. 12, pp. 1969–1980, Dec 2017.

[14] R. Inoue, D. Miyagi, M. Tsuda, and H. Matsuki, "High-efficiency transmission of a wireless power transmission system for low-frequency using rebco double-pancake coils," *IEEE Trans. on Applied Superconductivity*, vol. 27, no. 1, pp. 1–6, Jan 2017.