Inductive Power Transmission for Untethered Micro-Robots

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Abstract – **A new concept for inductive power transmission is proposed to transmit constant power over a large area of interest. This concept includes a specially designed winding group at the power transmitting side, which is similar to the windings in a linear motor. The winding group generates a traveling magnetic field over the complete working area. This magnetic field causes an alternating magnetic flux through a receiving coil that is located in this magnetic field and therefore induces an alternating voltage in the coil. The realized prototype transmitted maximum 330 mW DC power at the operating voltage of 3.3 V to the power receiver, which has the dimension of 11.5 mm x 11.5 mm x 4.0 mm, throughout a working area of 180 mm x 220 mm. Under different loads the output DC voltage of the power receiver varied from 2.6 to 5.1 V throughout the whole working area. A possible application of this method is powering of untethered micro-robots.**

I. INTRODUCTION

Constant wireless power transmission within a given working space is required by many applications, for example, in the field of robotics. In this application the robots must move in the working space without being hampered by power cables and meanwhile get a continuous and constant power from the power transmitter.

Different technologies can be used for wireless power transmission, such as solar cells, microwave transmission and inductive coupling.

Solar cells [1] can fulfill the requirement of homogeneous power transmission, but their low power output under standard light intensity limits their use in most applications. Although this drawback can be improved by directed light beaming [2], in which a light beam with high intensity is focused on moving targets, such systems are very complex because a tracking system is necessary for each moving target.

Similar to the light, microwave is another medium to transmit power wirelessly [3] [4]. However, the harmful microwave must be limited in a closed space. Moreover, the antennas and the corresponding regulation circuits increase the complexity and size of the power receiver.

Inductive coupling is also being used for wireless power transmission in different fields. A great amount of discussions and applications of transcutaneous links for implant systems based on the principle of air-core transformer for transmitting power, data or both have been published [5] [6]. This principle has also been used to supply power for moving parts in electroplating[7], vehicle industry[8], and sensor technology [9], where power cables are impossible or difficult to be realized. Inductive coupling allows to obtain high efficient and high power transmission. However, one problem in the current applications is that the power receiver has to be rather stationary in order to obtain a constant power because the power transmitter cannot effectively provide a constant magnetic field in a large area. This drawback could be overcome by special designs of the coil geometry of the power transmitter.

Within the frame of the project, “Miniaturized Co-operative Robots Advancing towards the Nano-Range” (MiCRoN) [10], supported by European Union, a patented concept of inductive power transmission [11] was proposed and a prototype system was realized to transmit constant and stable power to the miniaturized robots (MiCRoN-Robots), which have the size of roughly one cubic centimeter. The power receiver on a robot is required to be 11.5 x 11.5 x 4.0 mm^3 in the project. It should supply 300 mW power with around 3.3 V operating voltage constantly while traveling in the working area of about 20 x 20 cm^2.

II. PRINCIPLE

A. Fundamental Concept

Inductive power transmission depends on a changing magnetic field that is usually generated by a power transmitting coil and a receiving coil in this magnetic field. If the magnetic flux through the receiving coil is changed, a voltage will be induced in the receiving coil. The simplest way to generate a changing magnetic flux in the receiving coil is to actuate the transmitting coil by an alternating current. This principle has been used in the inductive power transmission so far.

An alternative to generate a changing magnetic flux in the receiving coil is to put the receiving coil in a traveling magnetic field. This concept is illustrated in Fig. 1. As shown in the figure, the magnetic flux ϕ through the coil at time t could be calculated with the equations,

$$\begin{aligned} \phi &= \int_{x_0-r}^{x_0+r} b \cdot H(x,t)\mathrm{d}x \\ b &= 2\sqrt{r^2-(x-x_0)^2} \\ H(x,t) &= H_0 \sin\left(\frac{2\pi}{a}x - vt\right) \end{aligned} \quad , \qquad (1)$$

where b is the length of the segment of line that is parallel to the y-axis cut in the coil, $H(x, t)$ is the magnetic field intensity, H_0 is the maximum value of the magnetic field intensity, and a is the wavelength of the magnetic field.

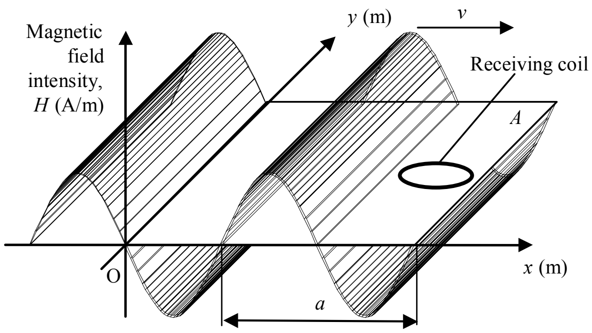

Fig. 1 Fundamental concept of inductive power transmission using moving magnetic field

The sine-form curved face represents the z-component of the magnetic field intensity in the plane *A* at time t_0. The curved face travels in the direction *x* with a speed *v*. The receiving coil with radius *r* is placed at point (x_0, y_0) in the plane. The traveling magnetic field produces a changing magnetic flux in the receiving coil.

B. Generation of the Traveling Magnetic Field

Analogous to a linear motor, the traveling magnetic field used for power transmission is generated by alternating currents flowing through a specially arranged winding group.

The winding group is composed of two electrically independent windings, each of which is wound according to the scheme shown in Fig. 2, so that the straight parts of the windings build a rectangular working area. The two windings are identical except that the second one is shifted in *x*-direction for *a*/4 offset compared to the first one.

If two alternating currents with π/2 phase shift flow through these two windings, respectively, a traveling magnetic field

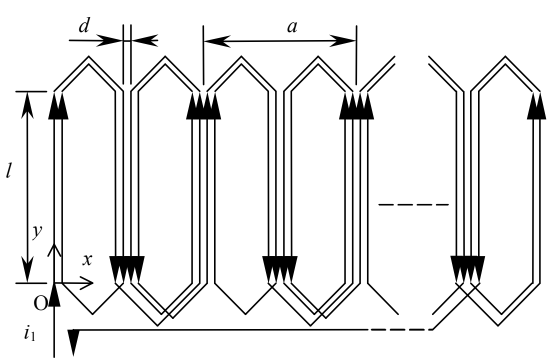

Fig. 2 A winding of the transmitting winding group

x-axis is vertical to the straight wires. *y*-axis is parallel to the straight wires. *z*-axis is perpendicular to the *xy*-plane directing upwards. The origin O is defined at the lower end of the left-most straight wire segment. Further definitions are: *l* – length of the straight wires of the coils; *d* – distance between the two neighbored wires; *a* – width of the basic element of the coils (or wavelength of the traveling magnetic field); *m* – number of the basic elements in the coils.

will be produced. These two currents are defined as:

$$i_1 = I_0 \sin(\omega t),$$
$$i_2 = I_0 \sin(\omega t - \frac{\pi}{2}). \tag{2}$$

The distribution of the magnetic field around the transmitting winding group was simulated with MATLAB based on Biot-Savart law as described with Fig. 3 and equation:

$$H = \frac{I}{4\pi} \int \frac{\sin(\theta)}{r^2} \mathrm{d}l , \tag{3}$$

where *H* is the magnetic field intensity at point P, d*l* is the infinitesimal length of the conductor carrying current *I*, *r* is the distance between P and d*l*, and θ is the angle between the current direction at d*l* and the line from d*l* to P. The direction of the magnetic field at point P is determined by the right hand rule.

Refer to Fig. 2, the *z*-component of the magnetic field intensity at point P(x_p, y_p, z_p) generated by the current in the wire that coincides with *y*-axis could be derived from equation (3):

$$H_z = -\frac{I \cdot x_p}{4\pi} \cos(\alpha) \int_0^l \frac{1}{r^3} \mathrm{d}y ,$$
$$r = \sqrt{x_p^2 + (y - y_p)^2 + z_p^2} \tag{4}$$

where α is the angle between *xy*-plane and the line connecting point P and the nearest point on *y*-axis. The minus sign of H_z means the magnetic field of this current is in the negative direction of *z*-axis. Based on this equation, the overall magnetic field at any point generated by all the straight wires of the power transmitting windings could be numerically calculated.

The calculation result is shown in Fig. 4, which provides only the magnetic component in *z*-direction because only this component contributes to power transmission.

The simulation results show that the magnetic field distributes homogeneously over the whole transmitting winding area. Outside of the winding area the field intensity decreases rapidly. That means, the magnetic field is concentrated in the vicinity of the windings. This feature

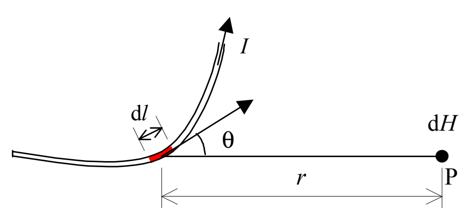

Fig. 3 Principle of Biot-Savart Law

The current in the infinitesimal length, d*l*, of the conductor carrying current *I* contributes the magnetic field component d*H* at point P. The whole field intensity is calculate with equation (3).

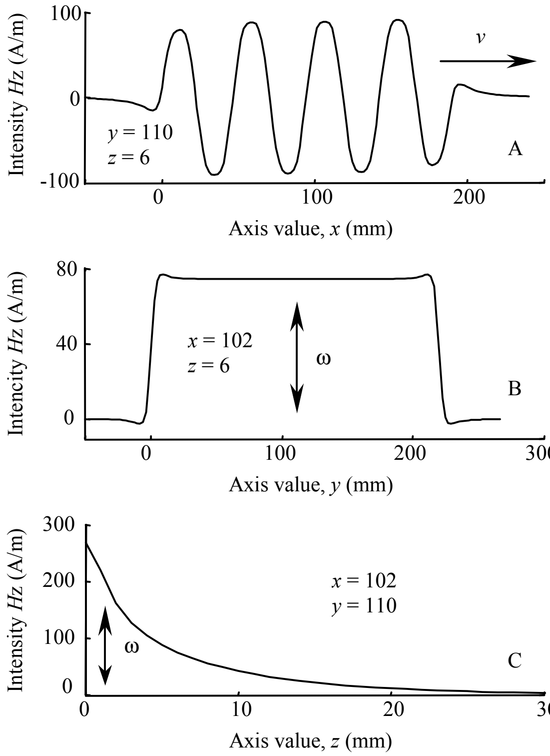

Fig. 4. *z*-component of the magnetic field intensity generated by the transmitting winding group along (A) *x*-, (B) *y*- and (C) *z*-direction

Traveling speed of the magnetic field $v = a\omega/2\pi$ (A). The curves (B, C) resonate between negative and positive maximum values with angular frequency ω.
Simulation parameters: $t = 0$, $l = 220$ mm, $d = 3$ mm, $a = 48$ mm, $m = 4$, wire diameter = 0.

reduces the magnetic interference to other electromagnetic systems around the power transmitter.

The traveling field generates an alternating magnetic flux through any small area that is parallel to the *xy*-plane of the winding group. This magnetic flux will induce an alternating voltage in a receiving coil to realize the power transmission.

III. SYSTEM CONFIGURATION

A. Transmitting Winding Group

The transmitting winding group is the core element of the power transmission system. The structure and prototype of the winding group are shown in Fig. 5. The winding method is illustrated in Fig. 2, where each straight line is fit into one groove in the winding holder. The first winding starts from groove 1 and the second winding starts from groove 5, such that the two windings have a *a*/4 spatial offset. Each winding has four basic elements. The winding group provides an area of 200 x 230 mm^2 that is formed with cupper wires.

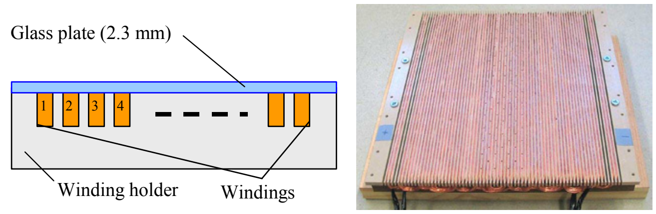

Fig. 5 Structure and prototype of the transmitting winding group

The windings are wound on a hard plastic holder with 240 mm x 240 mm area. 72 grooves are fabricated in the holder to hold the copper wires. The grooves are 1.5 mm wide and 4 mm deep. The groove pitch is 3.0 mm. The glass plate was not mounted in the photo of the prototype.

To obtain an effective power transmission several parameters must be optimized, including the winding element width, *a*, the operating frequency, *f*, and the wire structure.

The winding element width, *a*, directly influences the magnetic field intensity if other conditions are fixed. According to Biot-Savart Law, if the effective values of the currents keep constant, the magnetic field generated by the transmitting windings increases when parameter *a*, i.e., the distance between the straight segments of the windings, decreases. However, if value *a* becomes too small, e.g., less than two times of the receiving coil diameter, the receiving coil would receive both positive and negative magnetic flux all the time. This would reduce the net flux through the coil. Therefore, optimal value *a* has to be determined.

This was done using numeric calculation with MATLAB. The simulation result, illustrated with the relative relationship of magnetic flux through the receiving coil depending on ratio *a*/*r*, is shown in Fig. 6, where *r* is the average radius of the receiving coil. It can be seen that the highest magnetic flux occurs at $a/r = 5.4$. Based on the required dimension of the power receiver, *r* is designed as 7.75 mm. From the curve it is obtained that the optimal value $a = 42$ mm. Considering the convenience of mechanical fabrication, $a = 48$ mm is selected, where the flux reduces 5% compared to the best value of the

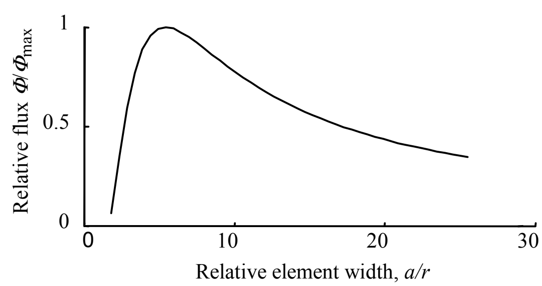

Fig. 6. Relative magnetic flux through the receiving coil depending on the relative width of the winding element

a is the width of a transmitting winding element, *r* is the radius of the receiving coil, Φ is the magnetic flux through the receiving coil.

calculation result.

Theoretically, the operating frequency should be as high as possible to increase the transmitting efficiency and to reduce the system volume. However, it can not be unlimitedly high because of the influence of the capacitance between the two windings. Since the windings are close to each other, or, they are actually embedded into each other, the capacitance is relatively large. This capacitance causes such a low impedance between the windings over a certain frequency that the transmitting circuit cannot work properly any more.

Because of the difficulty of theoretical analysis, the operating frequency was determined by experimental approach with the help of frequency-impedance curves that were measured with an impedance analyzer after the winding group had been wound. The selected frequency is 500 kHz. To reduce the capacitive coupling between the windings, a material with low dielectric constant should be considered for designing the winding holder.

In order to reduce the skin effect, 360 thin enamel wires each with 0.1 mm outer diameter are bound together to build one wire with the consideration of the mechanical strength. The electrical parameters of the completed transmitting windings are listed in Table I.

TABLE I
ELECTRICAL PARAMETERS OF THE TRANSMITTING WINDINGS AT 500 KHZ

	Inductance, L (μH)	Serial resistance, R (Ω)
Winding 1	10.51	0.62
Winding 2	10.62	0.53

B. Transmitting Side Configuration

The transmitting-side is composed of a signal generator, two class-E power amplifiers and a transmitting winding group. The whole configuration is shown in Fig. 7.

The signal generator is a simple digital circuit, which generates two square waves with $\pi/2$ phase difference to provide accurate timing signals to the class-E power amplifiers. Every winding is combined with the corresponding amplifier to work in series resonance mode.

Class-E amplifiers are used in this configuration because of their simplicity and high efficiency. The principle and application guides of this amplifier type are described in details in [12] and [13]. Accurate tuning of the parameters of the two class-E amplifiers results in two sinusoidal currents with $\pi/2$ phase difference in the two transmitting windings, respectively. Consequently, a traveling magnetic field will be generated around the transmitting winding group as described in the former chapter.

C. Receiving Side Configuration

The function of the receiving side is to pick up the energy stored in the magnetic field.

The realized power receiver is composed of a receiving coil, a serial resonance capacitor, a rectifier and a filter. The power receiver is design to fit into a frame of 11.5 x 11.5 x 4.0 mm^3 as required by the MiCRoN project. The circuit and structure of the power receiver are shown in Fig. 8.

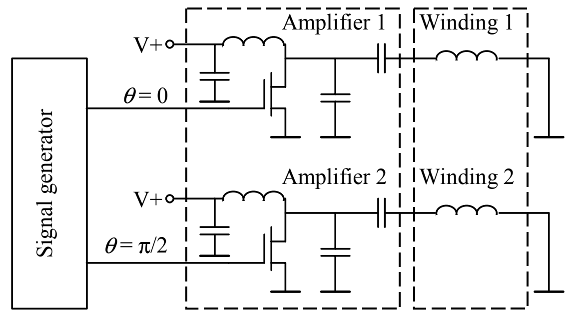

Fig. 7 Transmission-side configuration

Based on the almost fixed mechanical parameters, the number of coil turns is the most important parameter influencing the coil performance. With the fixed coil volume, the number of coil turns is inversely proportional to the thickness of the wire, with which the coil is wound, and thus directly proportional to the coil resistance. The determination of the turn number is to obtain sufficient output voltage at the power receiver with enough coil turns and meanwhile reduce the influence of the coil resistance. This should be optimized based on the magnetic field strength of the power transmitter and the specific features of the load on the receiving side.

The coil turns was determined by empirical optimisation with the guide of theoretical estimation. Receiving coils with different turns were fabricated and tested. The final determined value is 200 turns.

As in transmitting side, Litz wires composed of 30 thin enamel wires each with 0.03 mm outer diameter are used to wind the coil in order to reduce the skin effect.

Since the actual inductances of the coils show a variation, the resonance capacitor, Cr, must be carefully tuned to obtain an optimal resonance point.

IV. EXPERIMENTAL RESULTS

A. Distribution of Magnetic Field

The distribution of the magnetic field that is generated by the transmitting winding group was checked with the output

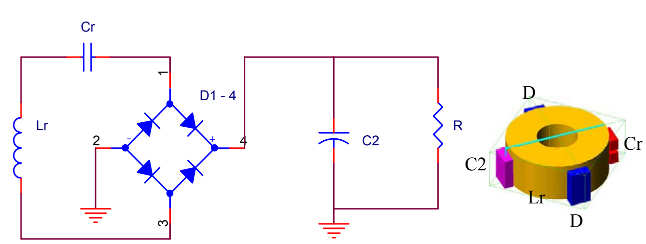

Fig. 8 Reception side schematic and a complete power receiver

DC voltage of the power receiver. The result is shown in Fig. 9 (refer to Fig. 2 for the definition of the coordination system). During the tests, the power receiver was directly put on the cover glass plate of the transmitting winding group.

From these curves it can be seen that the power receiver with a fixed load resistance of 33 Ω had a quit constant output voltage throughout the whole area of the power transmitting winding group. The maximum variation of the output voltage throughout the effect winding area of 180 x 220 mm^2 was 28% under this load. The lowest voltage was 2.6 V near the edge of the working area, and the highest voltage was 3.5V.

The receiver output voltages with load resistance of 10 kΩ showed that it had the same feature as those shown in Fig. 9 with the exception that the voltage values were increased due to lighter load. In summary, the lowest and the highest voltages throughout the working area were 4.1 V and 5.5 V, respectively.

B. Output Characteristics of the Power Receiver

The output characteristics of the power receiver was tested at the middle point of the transmitting winding group with different load resistance. The voltage and power curves are shown in Fig. 10. From the figure it can be seen that the output voltage of the power receiver changes from 3.3 to 5.1 V over a wide range of load resistance from 33 Ω to 10 kΩ.

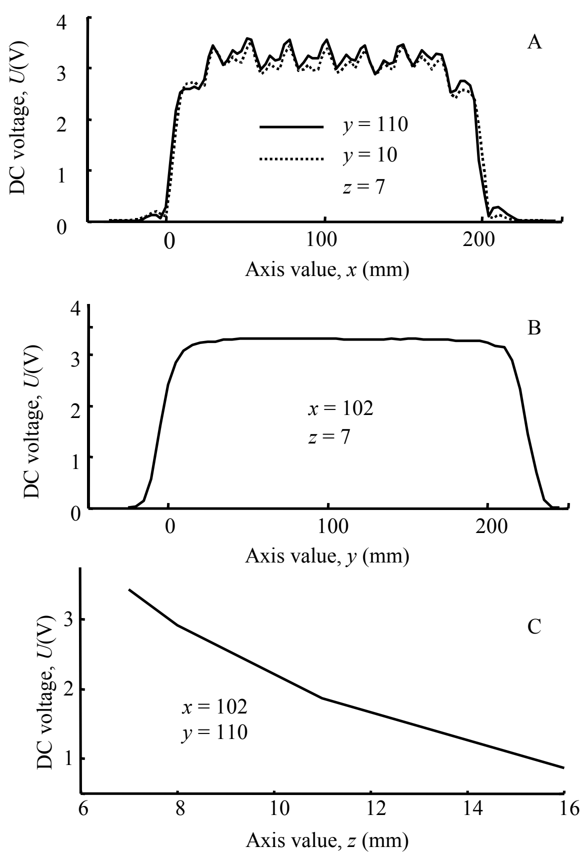

Fig. 9. Output DC voltage of the power receiver over the working area of the power transmitter

(A) along *x*-direction; (B) along *y*-direction; (C) along *z*-direction. The coordination of the middle point of the working area surface is (102, 110, 4) mm. The coordination of the receiving coil refers to its central point. Load resistance R = 33 Ω

Since the robot assembly has not yet been finished at the moment when this report was written, the test results using micro-robots could not be provided. However, according to the requirement of the micro-robots, the on-board electronics should work in the voltage range of 1.6 – 5.5 V. The test results showed to fulfill this requirement.

C. Efficiency of Power Transmission

The power transmission efficiency was estimated by comparing the input power of the power transmitter and the output power of the power receiver. During the test, the overall input power of the transmitter was kept around 26 W. The input power of the power transmitter didn't change significantly under different loads of the receiver. Therefore, the system efficiency depends on the output power of the power receiver. At a load resistance of 33 Ω, the power receiver output a power of about 330 mW, corresponding to a efficiency of about 1.27 %.

The low efficiency of the power transmission is caused by the low coupling coefficient between the transmitter windings and the receiver coil because of the large difference of their sizes. This is the cost of the constant power transmission over a large working area because the power transmitter has to maintain a sufficiently strong magnetic field over the working area whereas a power receiver covers only a small fraction of this area. This power transmission concept allows multiple robots operating in the working area to increase the efficiency with the factor that is proportional to the number of the robots. This is another benefit of this power transmission concept.

Theoretically, the magnetic field stores energy; it doesn't "consume" energy. The most power loss occurs in driving the power amplifier and the resistance of the winding group of the power transmitter.

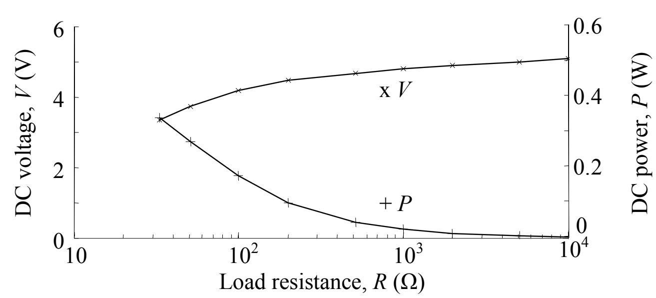

Fig. 10 Output of power receiver at different load resistance

V. CONCLUSIONS AND OUTLOOK

The simulation and test results showed that the wireless power transmission system can supply relatively constant power throughout a large working area. Multiple power receivers can operate at the same time on one power transmitter. As a cost of these features, this power transmission system has a relatively low efficiency.

Further optimization of this system could be carried out in order to reduce the power loss at the transmitting side and thus increase the efficiency of the whole system. Possible approaches include increasing the working frequency, careful selection of electrical components, selection of different materials for transmitting winding holder and so on.

VI. ACKNOWLEDGMENT

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