Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Autonomous Monitoring Aerial Robot System for Nuclear Power Plants

Ji H. Kim*, Beom W. Gu, Van X. Thai, and C. T. Rim
Dept. of Nuclear and Quantum Eng., KAIST, Daejeon 305-701, Korea
**Corresponding author: jihoonkim@kaist.ac.kr*

1. Introduction

After Fukushima nuclear accident, aerial robots (ARs) defined as unmanned aerial vehicles with actuators, automated controls and sensors are becoming viable solution for environment monitoring of nuclear power plants (NPPs) such as radiation detection and gathering samples [1]. ARs are essential for NPP accident management because human cannot access to the accident site due to the risks of unexpected explosions, collapses, and high level of radioactive contaminants. Moreover, ARs can support operators to manage normal operation of NPPs built in harsh environment of high temperature and humidity such as UAE Barakah NPP [2].

Because these ARs usually have very low energy capacity, however, the operation time of ARs is less than 30 minutes and should be recharged regularly by human powers, which makes it impossible to monitor NPPs by ARs automatically.

In this paper, autonomous monitoring aerial robot system (AMARS), which includes omnidirectional wireless charging platform, aerial robot, landing coils and a battery management board, is proposed to guarantee automatic monitoring of NPPs. The prototype of the system is fabricated, and omnidirectional charging of the system is experimentally validated with 1 C charging state.

2. Design of AMARS

2.1 Configuration of the Proposed AMARS

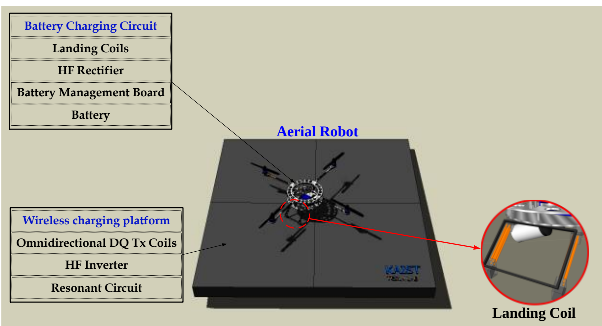


Fig. 1. Overall configuration of the proposed AMARS.

The proposed AMARS consists of the wireless charging platform and an AR with the battery charging circuit, as shown in Fig. 1. Wireless charging platform is composed of high frequency inverter, and omnidirectional D- and Q-coils, while battery charging circuit is composed of a landing coil, rectifier, and battery management board.

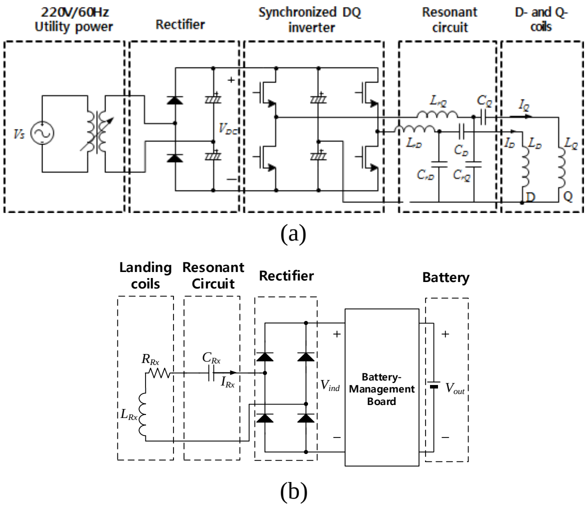


Fig. 2. Overall system circuit for (a) wireless charging platform, (b) battery charging circuit on the AR.

Equivalent circuit of the overall system is shown in Fig. 2. Each D- and Q- coils of the wireless charging platform is powered by synchronized D-Q inverter, which generates high frequency AC power from the rectified utility power, as shown in Fig. 2(a). Inductors of L_{rD} and L_{rQ} are inserted to regulate the current going through D- and Q- coils, and capacitors C_{rD}, C_{rQ}, C_D and C_Q are adopted to compensate the output reactance of the inverter. As shown in Fig. 2(b), the V_{ind} is defined as the rectified-induced voltage on the landing coil, which is the input voltage of the battery management board, and converted to the battery voltage of 12 V.

2.2 Operation Concept of AMARS

While a group of ARs is flying around the NPP to monitor the building, the other group of ARs is being charged to prepare their operation on each wireless charging platform, which is placed adjacent to the NPP building. When the flying group of AR has low remaining battery-voltage during its mission, it lands to its charging platform and the other group, which finished charging their batteries, takes off the platform to monitor the NPP continuously. The operation concept of the AMARS is shown in Fig. 3.

This AMARS enables the ARs to monitor NPP continuously and autonomously without any non-operating period of ARs, as it does not need human power to charge the batteries of ARs. The number of AR groups can be three or more to operate ARs efficiently.

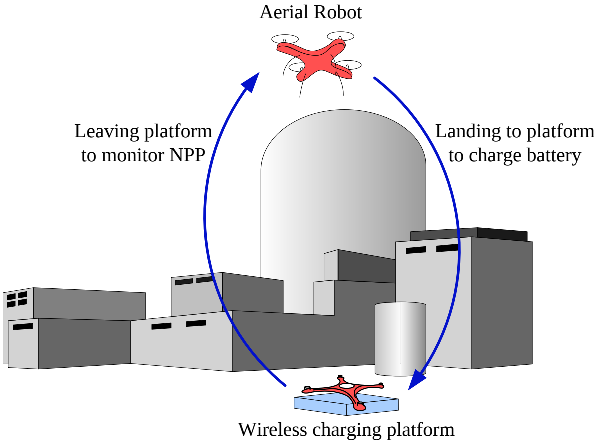


Fig. 3. Operation concept of the AMARS.

2.3 System Requirements of AMARS

When the AMARS is in operation, ARs land on the wireless charging platform to charge their battery, and leaves the platform to monitor the NPP environment repeatedly. In order to make the AMARS operation autonomous, the wireless charging platform should be able to charge the on-board batteries of ARs no matter where the AR lands on it. To satisfy the condition above, following system requirements should be met.

SR 1. The position of the landed AR shall be independent with the charging ability.
SR 2. The direction of the landed AR shall be independent with the charging ability.
SR 3. It should be resistant to water and radiation.

The resistance capabilities in SR3 are essential in order to deploy the AMARS under nuclear accidents. However, this paper mainly focuses on the omnidirectional wireless charging platform and landing coil to satisfy SR1 and SR2, which enables the AMARS to operate autonomously on operation of monitoring NPPs. To meet the SRs stated above, inductive power transfer system (IPTS) with DQ quadrature operation is adopted as the wireless charging platform [3].

2.4 Design of the D-, Q-, and Landing Coils

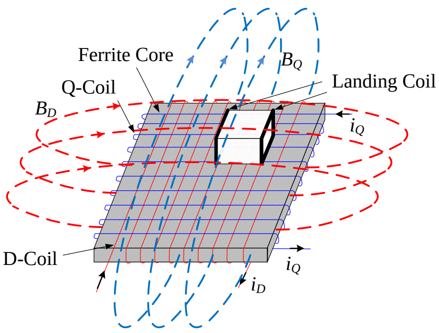
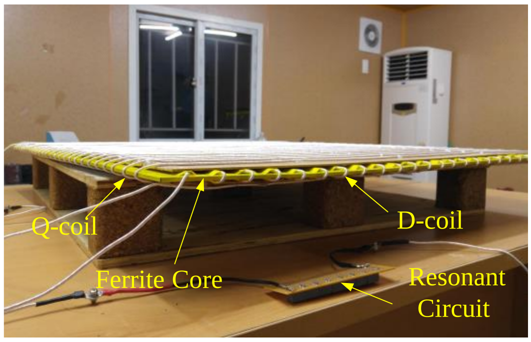


Fig. 4. Proposed wireless charging platform with landing coil.

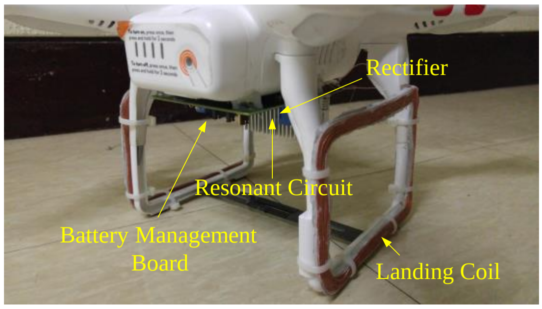
Proposed omnidirectional wireless charging platform is shown as Fig. 4. The wireless charging platform is composed of flat and wide ferrite core to make magnetic flux density stronger, and two coils, which are wound around the core to generate AC magnetic field. Each coil is wound horizontally and vertically to make two orthogonal magnetic fields of B_D and B_Q, and the currents of I_D and I_Q on each coil have 90 degrees of phase shift. This is to generate the rotational magnetic field on the platform. Landing coils are perpendicular to upper surface of the platform so that the induced voltage on the landing coil to be uniform with any position and direction on the platform.

3. Experimental Validation with AMARS Prototype

3.1 Prototype Fabrication of AMARS



(a)



(b)

Fig. 5. Fabricated prototype of (a) wireless charging platform (b) battery charging circuit.

Fabricated prototype of the wireless charging platform is shown in Fig. 5. The size of the wireless charging platform has been selected as 1 m × 1 m for landing of ARs where the phantom from DJI was used for the AR. The system has been designed to get the induced the induced voltage V_{ind} higher than 18 V on the landing coil; 18 V is a typical input voltage of battery management board, when both I_D and I_Q of the platform are controlled to be 1 A.

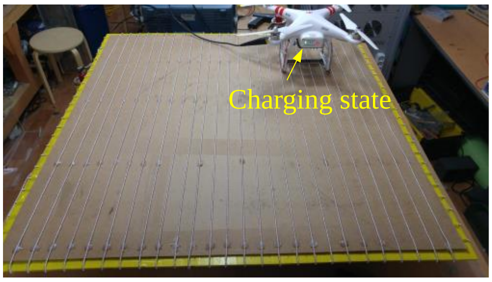
By taking into account a skin depth of 0.12 mm at the operating frequency of 280 kHz, a litz-wire with a strand diameter of 0.05mm is adopted. The parallel number of strands of the litz-wire is selected as 1300 for D- and Q-coils to ensure a current density lower than 400 A/cm^2 where the number of turns is selected as 25 for both D- and Q- coils. To wind the coils on the ferrite core with equal spacing, the pitch between each turn of the coils was designed to be 3.85 cm. For the landing coil, two coils of 30 turns are connected in series to increase the induced voltage, and the parallel number of strands of the litz-wire is selected as 40 to meet the current density of 400 A/cm^2. For Battery management board, BQ24650EM-639 from Texas Instruments was used where its input voltage and output voltage are designed to be 18 V and 12 V, respectively.

Parameter of circuit components selection are shown in Table I.

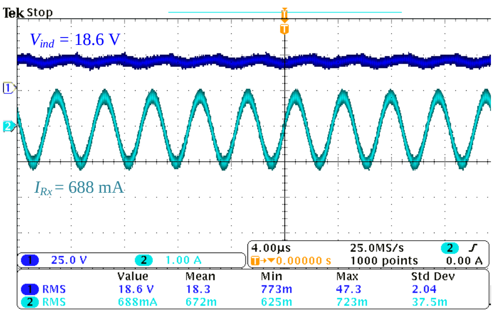
Table I: Parameter values of circuit components

Parameter	Value (unit)
L_{rQ}, L_{rD}	40 (uH)
C_{rQ}, C_{rD}	7.7 (nF)
V_{out}	12 (V)
R_{Rx}	7 (Ω)
L_D	936 (uH)
L_Q	775 (uH)
C_D	0.47 (nF)
C_Q	0.61 (nF)
L_{Rx}	490 (uH)
C_{Rx}	0.66 (nF)

3.2 Experimental Validation of AMARS



(a)



(b)

Fig. 6. Experimental verification (a) charging AR on the platform (b) waveform of voltage and current of landing coil.

In order to validate the omnidirectional charging of the system, the charging state of the on-board battery in AR was checked when the AR was placed on the corner of the wireless charging platform, as shown in Fig. 8.(a). At this point, the induced voltage V_{ind} on landing coil was measured as 18.6 V with current of 0.69 A in rms value, which means the 0.5 C charging considering a battery capacity of 2,200 mAh and battery voltage of 11.4 V.

4. Conclusion

In this paper, the concept of AMARS has been proposed and its performance was successfully verified with a fabricated prototype. The charging state of the on board battery in AR was measured as 0.5 C with the induced voltage of 18.6 V, which is well matched to the designed induced voltage when the AR was placed on the edge of the wireless charging platform. For further works, the design of the wireless charging platform for higher power level will be conducted for a quick charging state of the ARs. Furthermore, the optimization of the AMARS in terms of high efficiency and light weight of battery charging circuit is also left for further works.

REFERENCES

[1] A. Franchi, C. Secchi, H. I. Son, H. H. Bülthoff, and P. R. Giordano, Bilateral teleoperation of groups of mobile robots with time-varying topology, IEEE Trans. Robot. Vol. 28, pp. 1019-1033, 2012.

[2] J. K. Lee *et al.*, Assessment of wind characteristics and atmospheric dispersion modeling of ^{137}Cs on the BARAKAH NPP area in the UAE, Nucl. Eng. Technol. Vol. 46, pp. 557-568, 2014.

[3] Bo H. Choi, Eun S. Lee, Yeong H. Sohn, Gi C. Jang, and Chun T. Rim, Six degrees of freedom mobile inductive power transfer by crossed dipole Tx and Rx coils, IEEE Trans. on Power Electronics, Vol. 31, No. 4, pp. 3252-3272, 2015.