An Universal, Inductively Coupled Battery Charger for Robot Power Supplies

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Abstract

This report describes the design, construction and test results of an inductively coupled battery charger for robot power supplies. The system should be capable of charging several robot batteries at once from a contactless charging station.
The charger should be capable of providing different charging conditions to several different kinds of battery at once. The system should be capable of charging all of the popular rechargeable battery types in use today.
The system contains a bi-directional, half-duplex Inductive Power Transfer (IPT) communications channel.
The communications channel relays data between the charging station and the pickup. This allows the charging station to implement a smart charging algorithm based on current battery parameters measured on the pickup side. It also provides feedback to allow the charging station to regulate the total amount of power provided to the system, depending on the current requirements of the batteries on the charging station.
The communications system uses the same inductive link as the power transfer system and operates by modulating the data signal onto the power signal.

1 Introduction

The past ten years have seen an explosion in the use of small and medium sized battery powered devices. This includes autonomous robots like vacuum cleaning robots and pet robots, as well as cellular phones and PDAs.
A universal battery charging station could remove the need for a separate wire to charge each battery powered device. For autonomous robots it would provide the additional benefit of simpifying the navigation algorithm at charging time. Due to the contactless nature of inductive power transfer, the robot would only need to be near the charging station for its batteries to be charged.

Inductive Power Transfer (IPT) based systems have been used extensively in systems involving the transportation of people and materials[Boys and Green, 1995; Hu *et al.*, 2002c; Covic *et al.*, 2000]. They are especially useful in autonomous electric vehicles that stick to fixed tracks most of the time [Hu, 2001].

Inductive power systems have several useful qualities:
The contactless nature of IPT reduces the risk of electrocution because any exposed tracks or charging elements can be electrically insulated. This makes IPT attractive for transportation of people [Hu, 2001] and for home use.
Transportation systems using inductively coupled battery chargers already exist and may become more attractive in the future due to the renewed interest in electric vehicles.

IPT systems are relatively immune to dirt and dust and do not emit sparks. This makes them useful in dirty industrial enviroments and dangerous enviroments like coal mines. An IPT system is used for transportation of materials in the Daluita Coal mine in Northwest China [Hu *et al.*, 2002c].

However, because of the loose coupling of IPT systems and their relatively poor power efficiency they are generally only used for specialised high power applications where safety is the primary concern.

IPT systems are also useful where direct contact with tthe power supply is inconvenient. Low power, high frequency IPT systems are used extensively in biomedical implants for power supply and communications [Hu *et al.*, 2002a; Tang *et al.*, 1995]. Direct contact with the external power supply is highly undesirable in these applications as it would require wires to break the skin.

2 System Design

2.1 System Design Overview

The proposed system consists of a Charging Station (primary circuit) and multiple pickup circuits (secondary circuits) which need to be built into the robots' battery packs to acquire energy from the inductive link.
The design aimed to keep most of the complexity of the circuit on the charging station side to reduce the size and expense of the pickup circuits.
The charging station was required to charge the batteries of multiple robots simultaneously. Power conditioning circuitry on the pickups provided different voltage and current levels to each pickup as required.

A bi-directional communications channel was required to relay data between the charging station and the pickups. This was used to provide feedback on the battery charging algorithms required to provide optimum charging conditions to the batteries and to optimise the power output of the charging station. It also allowed status reporting to a PC.
Previous designs of this type have used radio or infrared links for communication between the pickups and the charging station [Covic *et al.*, 2000] or a separate coil for communications [Esser, 1995].
This system attempted to reduce the component count by modulating the data on the same signal as the power.
IPT communications channels of this kind have been used extensively in small, low power, high frequency telemetry systems, for example in biomedically implantable devices [Hu *et al.*, 2002a; Tang *et al.*, 1995].

2.2 Charging Station

The principle function of the charging station is to produce a high frequency sinusoidal current in the primary inductor (refer to Figure 1). This provides power to the air gap that forms the IPT link with the secondary (pick-up). A Current Fed Half Bridge Push-Pull Resonant Converter performs this function [Hu, 2001] (Figure 1 – Resonant Converter). This uses a Zero Voltage Switching Strategy to switch S1 and S2, in order to minimes switching losses [Hu, 2001]. The system operates at a frequency of 87kHz.

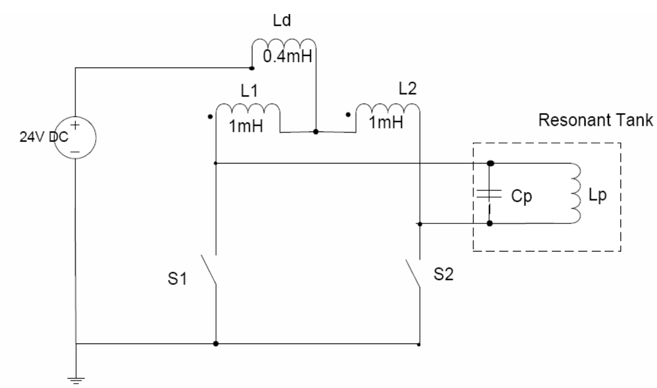

Figure 1 – Resonant Converter

Figure 2 shows a block diagram of the various components that make up the charging station.

A Buck Converter provides a variable DC input voltage to the Resonant Converter [Mohan *et al.*, 1995].
This has three main purposes: It allows the input power to be controlled depending on the amount of power required by the load at any particular time. It is used to provide amplitude modulation for the IPT communications channel. It is also a safety feature, as it ensures that the voltage supplied to the resonant converter will always vary slowly. The resonant converter may become unstable with sudden changes in input voltage [Boys *et al.*, 1999].

An Envelope Detector is used to detect communications from the secondary side. Communications signals from the pickups are modulated on the same waveform as the power. The output of this circuit must be suitable for serial input to the microcontroller.

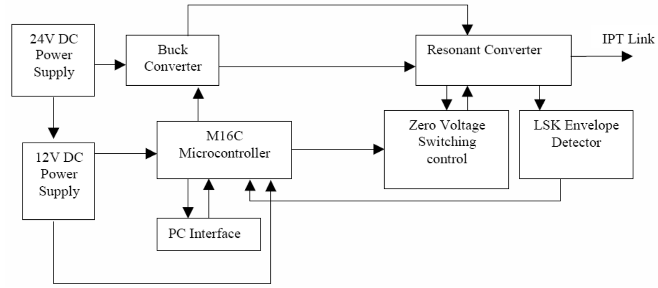

Figure 2 – Block Diagram of Charging Station

An M16 Microcontroller is used in the Charging Station. The Charging Station Microcontroller monitors and controls the battery charging algorithm. It must control the input voltage (by providing a PWM signal to the buck converter) to provide the pickups with enough power to charge their batteries.
It also encodes communications signals from the charging station to the pick-up and decodes data sent from the pick-up to the charging station. The M16C microcontroller is capable of communicating with a PC to provide the user with information on the charging process.

2.3 Pickup

The primary function of the pickup is to obtain power inductively from the air gap between the charging station and the pickup. This power must be conditioned to provide the correct charging conditions to the battery pack.
The proposed system would contain multiple idential pickup circuits. Therefore, when designing the pickup, emphasis was placed on reducing the size, cost and complexity of the circuit.

Figure 3 shows a block diagram of the various functional blocks comprising the pickup. Figure 4 shows a simplified schematic of the pickup circuit.

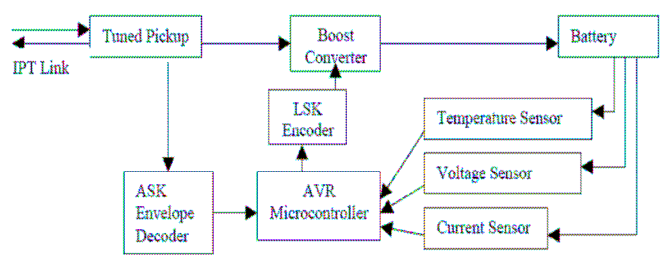

Figure 3 – Block Diagram of one Pickup

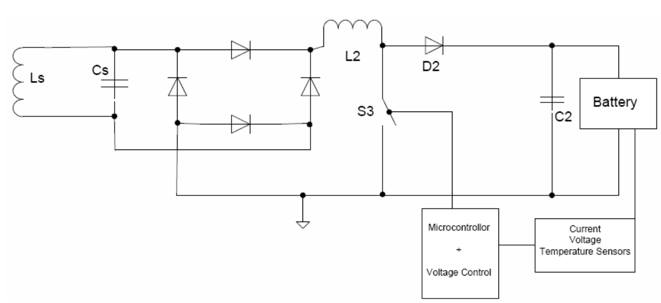

Figure 4 – Simplified Schematic of the Pickup Circuit.

The Pick-Up is tuned to the frequency of the resonant power supply (f_o) using a simple LC circuit and thus obtains power from the air gap. The natural frequency of the LC circuit is calculated using the following equation:

$$f_0 = \frac{1}{2\pi\sqrt{L_p C_p}} \qquad (1)$$

where **Lp** = Primary Inductance (H)
Cp = Primary Capacitance (F)
fo = Undamped natural frequency

The theoretical maximum power transfer to the pickup is given by the following equation [Boys *et al.*, 1995]:

$$P_{\max} = \frac{I_s^2 M^2 Q_2 \omega}{L_s} \qquad (2)$$

where $\mathbf{Q_2}$ = Quality Factor = $\omega C_s R_2$
M = Mutual Inductance of the primary and secondary inductors
$\mathbf{L_s}$ = Secondary Inductance (H)
and [Boys *et al.*, 1999]

$$I_s = \frac{j\omega M}{Z_s} I_p \qquad (3)$$

The AC current induced in the tuned LC circuit is rectified using a standard full bridge rectifier to produce a DC voltage (Figure 4).

This DC voltage is conditioned by a Boost converter to provide appropriate DC voltage and current levels to the battery [Mohan *et al.*, 1995].

A Load Shift Keying (LSK) Encoder [Tang *et al.*, 1995] and an Amplitude Shift Keying (ASK) Decoder are used to transmit and receive communications to and from the charging station. These will be discussed in greater detail in the following sections.

A range of sensors is used to monitor the charge status of the battery. The output of these sensors is fed to the AVR Microcontroller on the pickup which transmits the data to the microcontroller on the charging station. Using information from the sensors, the microcontrollers control the level of current transferred to the battery to ensure that it receives optimum charging conditions at each stage of the charging process.

3 IPT Communications System

A bi-directional communications system is required between the charging station and the pickup to allow the charging station to control the charging process based on battery parameters measured on the pickup side.
In this system communications signals are encoded onto the waveform that provides power to the air gap.

Communication from the primary side to the secondary is implemented by switching the power signal at the output of the resonant converter between its normal level and a lower level which is detectable by the pickup but still provides enough power to control the pickup microcontroller. This process is called Amplitude Shift Keying (ASK). This is achieved by varying the output voltage of the buck converter (refer to Figure 2) which provides an input DC voltage to the resonant converter.

Communication from the secondary to the primary is achieved by a process called Load Shift Keying (LSK) [Tang *et al.*, 1995]. This involves varying the loading on the pickup.
Any load on the pickup will reflect a voltage on the primary circuit proportional to the load. Therefore a variation in the load on the pickup can be detected by the charging station [Tang *et al.*, 1995].
The communications system must provide two discrete levels of voltage reflected onto the primary side, to represent the on and off states for digital communications. The difference must be easily detected on the primary side to provide a robust communications channel.

Signals are decoded by simple filters and comparators which feed a digital signal to the microcontrollers.

A simple Master-Slave communications protocol is used, since the communications channel is half-duplex. In a Master-Slave communications protocol the Master (the Charging Station) sends a message to all the Slaves (pickups) and requests a response from a specific pickup. Each pickup is assigned an ID number for communications purposes.

The maximum data transfer rate of this system is relatively slow but probably adequate for our purposes. In this system not much data needs to be transferred as battery charging is a slow process where the measured parameters increase gradually.

3.1 Communications from Primary to Secondary

In this system amplitude modulation is achieved by altering the input voltage (Vin) provided to the resonant converter, since the output voltage of the resonant converter is directly proportional to the input voltage (refer to Figures 1, 2). The peak voltage on the resonant circuit is given by [Hu, 2001]:

$$\hat{V}_{Lp} = \pi V_d \qquad (4)$$

where V_d = DC input voltage
V_{Lp} = Peak voltage across the primary inductor (Lp)

The input voltage to the resonant converter is switched between its nominal value (usually 24V) and a much lower value (12V, usually half the normal value).

When Vin is switched to its lower value, the change in power transfer will easily be detected on the secondary side but enough power will still be transferred to provide power to the microcontroller on the pickup. Voltage regulation on the pickup allows the microcontroller to continue to operate.

With amplitude modulation, the speed is limited by the response time of the resonant circuit to changes in input voltage. Another way of achieving this would be to detune the resonant circuit on the primary side by switching in another capacitor. This would be detected on the pickup as a reduction in power transfer. This process is known as Frequency Shift Keying (FSK) [Tang *et al.*, 1995]. It may be possible to increase the switching frequency and reduce the component count on the Charging Station in this way. However, this would require a fast, high side, AC switch which may be impractical.

Phase Shift Keying (PSK) is another option [Hu *et al.*, 2002a]. This could allow full-duplex communications but requires more complex modulation and demodulation circuits.

The data is encoded at a frequency of 150Hz (300bps). This frequency is relatively low, however it is adequate for the purposes of this system because not much data needs to be transferred.

The system is fairly slow because the voltage at the output of the resonant tank (refer to Figure 1) cannot change immediately. A certain amount of energy is stored in the resonant tank and this energy takes some time to dissipate. Therefore, the voltage across the resonant tank will always change relatively slowly. The slow change in voltage at the output of the buck converter will also introduce a certain delay to the communications channel.

3.2 Communications from Secondary to Primary

Communications from the pickup to the charging station are encoded by altering the voltage reflected from the pickup onto the primary side. In this direction, the modulation options are limited because under normal operating conditions, no power is transferred from the pickup to the primary.
It was mentioned previously that a load on an IPT pickup will reflect a certain voltage onto its primary power supply. The value of the reflected voltage is given by equation 5 which is shown below [Boys *et al.*, 1999].

$$V_r = \frac{I_1 \omega^2 M^2}{Z_s} \quad (5)$$

$$V_r \approx \frac{M^2 I_1 R_2}{L_2^2} \quad (6)$$

Where Zs is the load impedance on the secondary.
This reflected voltage acts like a small resistance in series with the primary inductor (Lp – refer to Figure 1).

If the resonant circuit on the pickup is short-circuited, no power will be transferred to the load meaning that the voltage reflected on the primary side decreases dramatically. In this system, communications signals are produced by the switching of a MOSFET (S3 – refer to figure 4) which effectively short circuits the tuning circuit for short periods of time. Figure 4 shows a simplified diagram of the pickup showing the position of S3.
S3 also forms part of the boost converter used to control the power flow to the load. In this capacity S3 is controlled by a PWM signal from the pickup microcontroller, which controls the voltage at the load by altering the duty cycle of the signal.

For the communications channel to be able to operate at the same time as the boost converter, using the same control switch, it must operate at a very different frequency. In this way the output signal can be filtered to remove the effects of the Boost converter's PWM signal from the data signal received on the primary side. In this system, the PWM signal runs at a frequency of 33kHz while the communications signal is encoded at 150Hz.

3.3 Communications Protocol

Because of the generally low reliability of wireless data transmission (especially when combined with power transfer) it was important to ensure that any errors can be detected in software. A robust protocol, supporting multiple devices and including error detection and device discovery, was implemented.
The link-layer interfaces for the channel are standard UART ports. This simplifies implementation as nearly all microcontrollers have UARTs. UARTs are active-low devices and are configured to use an 11-bit packet. This consists of one start bit, eight data bits, one even parity bit and one stop bit.

4 Results

A functioning prototype of the charging station and one pickup circuit was constructed to investigate the proposed design. Some of the circuit parameters of the prototype are displayed in Tables 1 and 2.

Parameter	Expected Value	Actual Value
Operating Frequency	88 kHz	87 kHz
DC Supply Voltage	24 V	24 V
Primary Tank Inductance	16 uH	15.9 µH
Primary Tank Capacitance	200 nF	200 nF
DC Leakage Inductance	0.4 mH	0.4 mH
Split Winding Inductance	1.0 mH	1.0 mH
Primary Tank Voltage	75.36 V_{PEAK}	76 V_{PEAK}
Primary Tank Current	9.15 A_{PEAK}	8.74 A_{PEAK}k
Initial Tank Current	0.24 A	-
MOSFET Startup Time	4 µs	4 µs

Table 1 – Primary Circuit Parameters

Parameter	Value
Tuned Frequency	84.8 kHz
Secondary Inductance	0.8 µH
Secondary Capacitance	4.4 µF
Secondary Quality Factor (2Ω load)	4.7
Secondary Open Circuit Voltage	8.1 V_{RMS}
Secondary Short Circuit Current	1.99 A_{RMS}
Maximum Power Transfer	16.1 W

Table 2 – Secondary Circuit Parameters

4.1 Power Efficiency

Overall power efficiency was measured with varying loads on the pickup. Passive loads were used to test power efficiency because batteries present a varying, unpredictable load to the pickup. Power efficiency was tested using three different resistive loads and three different duty cycles on the boost converter of the pickup (varying the duty cycle varies the amount of current

delivered to the load).
Efficiency is calculated by dividing the power delivered to the load by the total input power.

$$\eta = \frac{V_{out}^2 / R_l}{V_{in} I_{in}} \qquad (7)$$

The maximum power efficiency was found to be 36%. This is fairly low but it is expected that this could be improved by improved tuning and circuit design.
The maximum power transfer to one pickup was found to be 16W. Again, this could be improved by more careful tuning and circuit design.
If necessary efficiency could be improved by eliminating the buck converter from the circuit and using alternate methods of power control and amplitude modulation.

In general, operating systems at high frequencies is associated with reductions in power efficiency. High frequency operation is generally associated with high switching losses and heating of components. Although the maximum theoretical power transfer capabilities of the system increase with frequency the overall efficiency of the system is likely to decrease.

4.2 IPT Communications

The modulation index of the backwards and fowards communications channel was measured and calculated at different frequencies. In each case, the same load was presented to the pickup.
The modulation index indicates the degree of change in the amplitude of the carrier signal between the two binary digits (refer to Figure 5). A high modulation index indicates an easily detectable signal.

$$ModulationIndex = \frac{Voltage_{high}}{Voltage_{low}} \qquad (8)$$

Where $Voltage_{high}$ = Voltage Level Representing Binary Digit 1
$Voltage_{low}$ = Voltage Level Representing Binary Digit 0

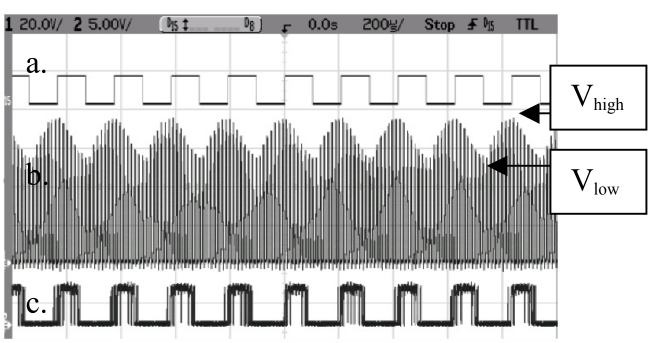

Figure 5 -Oscilloscope waveforms-
A. Data signal to be modulated on the power waveform
B. Data signal modulated on the power waveform
C. Data signal demodulated from the power waveform

Table 3 shows the measured modulation index of the signal from primary to secondary at varying frequencies. The modulation index is fairly low when the frequency reaches 1200Hz.

Baud	Frequency (Hz)	No Load Index	Average Load Index
300	150	21%	25%
600	300	11%	23%
1200	600	6%	16%
2400	1200	4%	9%

Table 3 – Modulation Index Measured from Communications Signal from Primary to Secondary

Amplitude Shift Keying (ASK) is likely to prove slower than other methods of signal modulation. In order to change the amplitude of the power signal, a certain amount of energy needs to be dissipated from the resonant tank on the charging station. This system uses a buck converter to implement amplitude shift keying. Buck converters have a fairly high response time which adds extra delay to the data signal.

Table 4 shows the modulation index for communications from Secondary to Primary at varying frequencies. This shows that the modulation index of the data signal varies non-linearly with frequency and is still adequate at frequencies up to 14400bps. It is therefore possible that these signals could be detected at much higher baud rates than the ones used in this system.

Baud	Frequency (Hz)	Index
300	150	15%
600	300	13%
1200	600	19%
2400	1200	22%
4800	2400	25%
9600	4800	44%
14400	7200	29%
28800	14400	10%

Table 4 – Modulation Index Measured from Communications signal from secondary to primary

The full IPT communications system was tested by sending a large amount of data backwards and forwards over the IPT link and recording the received data through the PC interface.

Testing was conducted using varying packet sizes to determine whether packet size affected the accuracy of the system. Testing was also conducted with varying loads on the pickup. The size of the load on the pickup has the potential to affect the accuracy of communications in both directions, as it will change the modulation index of the communications channel.
Data sent from the secondary to the primary is encoded by varying the load reflected from the secondary to the primary. Therefore, the maximum change in loading depends on the magnitude of the secondary load at any particular time.
Data sent from the primary to the secondary is detected by sensing changes in the voltage across the load current sense resistor on the secondary. Therefore varying the load will have a significant effect on the detectability of the communications signal.

Table 5 shows accuracy test results for communications from the primary to the secondary. Three separate tests were performed using three different packet sizes. The tests were repeated three time using a small, medium and heavy load on the pickup.

High Current (70% Duty Cycle on the Pickup)			
Packets Sent	Bytes Sent	Bytes Received Correctly	%Byte Errors
275	275	274	0.4
220	1540	1540	0.0
235	2350	2350	0.0

Medium Current (45% Duty Cycle on the Pickup)			
Packets Sent	Bytes Sent	Bytes Received Correctly	%Byte Errors
250	250	246	1.6
260	1820	1819	0.1
270	2700	2670	1.1

Low Current (30% Duty Cycle on the Pickup)			
Packets Sent	Bytes Sent	Bytes Received Correctly	%Byte Errors
250	250	247	1.2
260	1820	1818	0.1
260	2600	2600	0.0

Table 5 – Accuracy of communcations from Primary to Secondary.

Table 6 shows accuracy test results for communications from the Pickup to the Primary.

This table shows that the accuracy of communications from secondary to primary is slightly lower than communications from primary to secondary. The maximum byte error rate of the system is 3.0%. This is significantly higher than the maximum byte error rate for communications from primary to secondary which is 1.6%.

High Current (70% Duty Cycle on the Pickup)			
Packets Sent	Bytes Sent	Bytes Received Correctly	%Byte Errors
300	300	295	1.7
310	2170	2109	2.8
330	3300	3204	2.9

Medium Current (45% Duty Cycle on the Pickup)			
Packets Sent	Bytes Sent	Bytes Received Correctly	%Byte Errors
305	305	301	1.3
290	2030	1974	2.8
260	2600	2539	2.3

Low Current (30% Duty Cycle on the Pickup)			
Packets Sent	Bytes Sent	Bytes Received Correctly	%Byte Errors
330	330	321	2.7
330	2310	2240	3.0
320	3200	3108	2.9

Table 6 – Accuracy Test Results for Communications from Secondary to Primary.

Although the maximum speed of communications achieved in this project is fairly low at 150Hz, testing indicates that improved receivers and decoders could substantially increase the frequency. At much higher frequencies the modulation index of the communications channel is still adequate. Using some digital communications designs, dealing with higher error rates isn't difficult.

5 Conclusions

A universal, contactless, battery charging system was proposed for robot power supplies. The proposed system is capable of charging several different types of battery at once, providing different current and voltage levels to each of the different batteries.

A bi-directional IPT communications channel was proposed to allow power feedback to the charging station based on battery parameters measured on the pickup. This was implemented by modulating the data signal onto the power waveform.

A working prototype was constructed with a charging station and one pickup.

Although the prototype was functional, the maximum power efficiency was fairly low at 36%.

The bi-directional IPT communications channel was implemented successfully. A maximum byte error rate of 1.6% was recorded in the forwards direction and 3.0% in the backwards direction.

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