Systems for Human-Powered Mobile Computing

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ABSTRACT

This article outlines several projects aimed at generating electrical energy by passively tapping a variety of human body sources and activities. After summarizing different energy harvesting modalities and techniques, I spotlight work done in my research group at the MIT Media Laboratory, including a system that scavenges electricity from the forces exerted on a shoe during walking. This system uses a flexible piezoelectric foil stave to harness sole-bending energy and a reinforced PZT dimorph to capture heel-strike energy. The piezoelectric generators drive a battery-less, active RF tag, which transmits a short-range wireless ID while walking, thereby enabling location based services and active environments. Other systems that we have developed are also discussed, including a battery-less pushbutton that can send an RF ID code with a single push, sensor nodes that harvest mobility rather than energy, and power management schemes that exploit sensor diversity to achieve energy efficiency.

Categories and Subject Descriptors

B.8.0 [**Hardware**]: General

General Terms

Performance, Design, Experimentation, Human Factors.

Keywords

Energy Harvesting, Power Scavenging, Parasitic Power.

1. INTRODUCTION

As people carry increasing quantities of mobile appliances around with them, technologies that promise operation without requiring frequent battery replacement or recharging become attractive. Accordingly, the idea of unobtrusively tapping some fraction of the excess energy available from everyday human activity for this purpose has recently gained in popularity. This paper discusses systems that have been developed and fielded toward this aim. In addition to the other citations at the end of this paper, readers are pointed to the author's recent book chapter [1] and overview article [2] for more details and reference sources on this topic.

As tabulated in [1], the typical adult human expends roughly between 100 watts (resting) and 1000 watts or more (strenuous exercise). Although it is tempting to think that it would be easy to purloin a few watts from this reservoir, this energy is usually far from free. For most activities, the human body tends to streamline its energy expenditure, hence a designer must be very careful in extracting power, lest the drain on the user become noticeable and obtrusive.

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On the other hand, having humans actively drive generators used to power electronics (e.g., pedaling, cranking, pulling, etc.) can easily produce powers that range from a few watts (using arms) to tens of watts (using feet), at least until the subject become fatigued [1,2,3].

2. METABOLIC SOURCES

In [4], Starner tabulates different estimates of the energy available from various kinds of human movements and bodily sources that might be "parasitically" siphoned off. These are useful, although somewhat optimistic, numbers that are ideal for starting a discussion. Starner estimates 370 mW to be available from blood pressure, 400 mW to be available from exhaling, and 830 mW to be available from breathing, but these sources of energy are avoided in this paper, as it's generally impractical and potentially dangerous to tap into them. That said, research by Heller and collaborators works towards producing glucose/O_2-powered fuel cell "stents" for *in vivo* energy generation from the blood stream [5]. Small amounts of power could available (e.g., up to 1 mW in a 1 cm long by 4 mm wide device), although much work remains on building biologically transparent electrodes that can support long-term operation without dedgradation from biofouling (an equivalent-sized battery can last for up to a few weeks before discharging). Applications of such low-power, *in-vivo* sources include things like implantable biosensors or electromechanical devices like a valve to relieve incontinence.

Body heat suggests a quiescent reservoir of human energy. The low temperature difference between the body and its typical environment, however, cause the properties of existing thermoelectric materials and the overall Carnot limit to restrict the conversion efficiencies to within a percent or so – to make matters worse, the body also tends to constrict blood vessels in an area with excess heat transfer to limit heat loss. Nonetheless, low-power thermoelectrically-driven products have appeared. Produced during the 1990's, the Seiko Thermic™ wristwatch [2] used ten thermoelectric modules to generate a microwatt or so to run its mechanical clock movement from the small thermal gradient provided by body heat over ambient temperature. Applied Digital Solutions' Thermo Life® is a thermoelectric generator measuring 0.5 cm^2 in area by 1.6-millimeter thickness. Comprising a dense array of low-temperature thermopiles, it can generate 10 μA at 3 V (6 V open circuit) with only 5° C of temperature difference [6]. The ThermoLife® is designed for powering low-current biosensor electronics when in contact with the skin. These systems typically come with batteries that store extra energy produced during periods of higher temperature differences so they can continue to run during warmer, less efficient ambient temperatures.

3. INERTIAL REACTION GENERATORS

As people often wave their arms when working and walking, wrist-mounted platforms are appropriate locations for energy scavenging – indeed, commercial self-winding wristwatches have tapped this source for nearly a century [1,2]. A modern self-winding wristwatch contains an approximately 2-gram rotary proof mass mounted off-center on a spindle. As the user moves during the day, the mass reacts inertially, spinning and winding the mechanism. Electronic self-winding watches use the motion of this proof mass to drive a magnetic generator directly, or pulse the generator at its optimal rate after enough energy has been stored in a spring. These systems generally produce less than 10 microwatts under normal motion, but can deliver up to a milliwatt if the hand is shaken hard. Scaling them to higher power can involve using a proportionally heavier proof mass, which can become noticeable and cumbersome. As most people tend to spend the bulk of their time either immobile or in relatively inactive states [7], such body-worn generators tend to be driven sporadically.

The MEMS community has produced a wide variety of microgenerators aimed at energy scavenging for wireless sensor nodes – these devices have included electrostatic, magnetic, and piezoelectric generators. Although some of these devices have been aimed at body-worn applicatons [8,9,10], they tend to be resonant at frequencies ranging from several hundred Hz to several kilohertz, far above the primary Hz-level excitations found in walking and typical human movement, where the rotary-magnetic self-winding watches are hard to beat. That said, some speculative research is beginning on exploring rotational energy harvesting at the MEMS scale, building what are in effect tiny control-moment gyroscopes running in reverse [11].

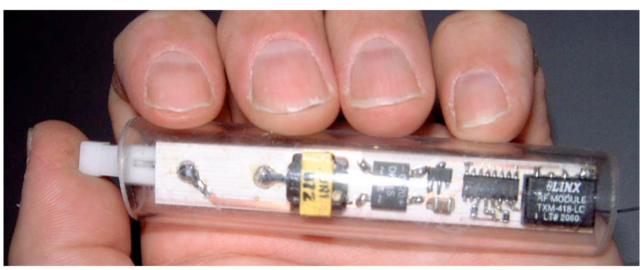

Figure 1: The MIT Self-Powered RF Transmitter Pushbutton.

4. HARNESSING ISOMETRIC FORCE

In many scenarios, forces that people apply against reacting surfaces can be tapped to generate significant energy. This kind of activity ranges from typing to walking, or exploits exoskeletons that press one body part against another.

In 2001, Paradiso and Feldmeier demonstrated pushbuttons that produce roughly 1 mJ of energy at 3 V per 15 N push (Fig. 1) [12]. In order to achieve this, they utilized a commercial piezoelectric striker coupled to an amorphous-core stepdown transformer from an electronic flash with a resulting LC resonance that was tuned to match the mechanical resonance of the piezoelectric element in the striker. One press of the button produced enough energy to generate and transmit more than six repetitions of a 12-bit ID code across a radio link over a large radius (i.e., 100 feet), as indicated in Fig. 2, even though most energy was wasted in a series regulator. Such devices enable remote controls, keyless entry systems, or generic switches to be designed without needing wiring or batteries. Another version of a self-powered piezoelectric radio button is now marketed in Germany by a company called EnOcean, which uses a bistable piezoelectric cantilever that snaps when pressed and released, conditioned by a switching regulator. We have seen this device produce about 100 μJ per 8N push at 3.3 Volts.

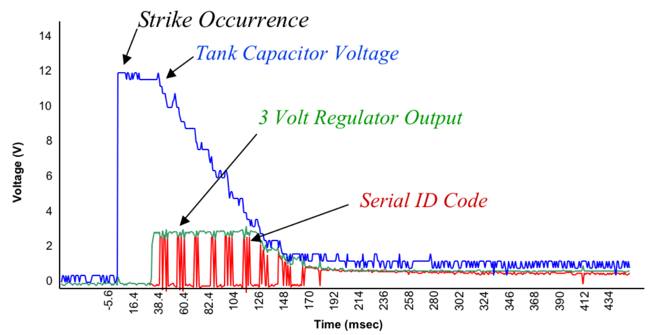

Figure 2: Waveforms from the MIT Self-Powered Switch, showing the transformer output voltage, the regulated supply, and the ID encoder's serial output line.

The most natural place to innocuously tap power from human activity would be from walking, as reviewed in detail in Ref. [1]. Extracting lots of power from the gait would fatigue the pedestrian (the muscles often work like springs, returning energy that is stored during the compressive part of the stride), but looking at standard jogging sneakers, which have soles that compress on the order of 1 cm, it is speculated that an adult of average weight could supply up to 7 watts of scavenged energy – restricting ourselves to safer margins, we can surmise that a watt or two could be realistically harvested.

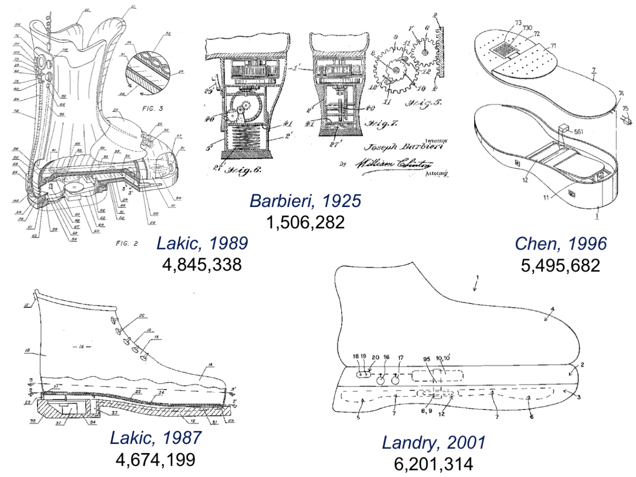

Figure 3: Some shoe generators in the US patent literature.

Extracting power from shoes has a long legacy in the work of inventors – as Fig. 3 suggests, the US Patent Library has records of shoe-powered systems (mainly driving boot warmers, although some with external power connectors for subsidiary systems) that go back to the early vacuum tube era. These systems tend to be all based around rotary magnetic generators driven by gears or hydraulics. Although shoe-mounted rotary generators are capable of achieving powers approaching several watts, they are often quite fragile because of the high gear ratios required, small input stroke, and harsh nature of the shoe environment. Fig. 4 shows two shoe generators developed by Paradiso and his team in the late 90's [13,14]. The device at left is a graft of a commercial squeeze-powered generator onto a shoe. Although not optimized for easy walking, average powers of a quarter-watt were achieved over a standard gait. The device at right was embedded entirely into the insole of a running sneaker. Because it had no flywheel (as in the design at left) or spring to store additional energy from the heel strike, all power needed to be converted directly at the footfall, leading to a reduced energy harvest that produced average powers on the order of 60 mW.

A set of generator shoes was developed by Antaki and collaborators in 1995 that drove piezoceramic elements mounted in a large sole at their resonant frequency via a passive flapper valve akin to a phase cannon [15]. Aimed at powering artificial organs, they achieved a power harvest ranging from 200-700 mW, although their bulk appeared to make continual walking potentially difficult. In 1998, Paradiso and collaborators demonstrated an energy harvester with generating elements embedded entirely within an insole (Fig. 5) [13,14]. Using a 16-layer laminated PVDF bimorph stave under the toes and midsole to harvest shoe bend with a clamshell-like back-to-back pair of flexible PZT unimorphs [16] under the heel to harvest strike, average powers on the order of 10 mW were collected. By integrating this energy on a storage capacitor, the shoes were able to directly power a radio that transmitted a 12-bit digital ID code with every few steps (Fig. 6). Although subsequent development of a switching regulator improved the efficiency of the impedance conversion [13], the power available from these simple pliant and nonresonant piezoelectric elements remained low, although interference with gait and the impact on the shoe (aside from a heel-mounted card for power conditioning and RF transmission that could be massively miniaturized) were minimal. Recent work by SRI international on developing shoes with heels made of rubbery dielectric elastomers has demonstrated average powers of 700 mW, although these require several kilovolts to be applied across the elastomer element (which works as a dynamic capacitor), and attaining longevity beyond the order of 100K footsteps is an issue that requires additional research.

Looking at power available elsewhere on the body, Rome and colleagues at the University of Pittsburgh have recently exploited the up-and-down motion of a hiker's hips relative to their backpack to drive a magnetic generator – when wearing a 38 kg backpack, users were able to generate over 7 watts [17]. Although this is an impressive harvest, a backpack of this mass is generally in the exclusive domain of serious hikers or military personnel. (Note - this is a reaction force generator - See Sec. 3)

An issue that pervades most of these approaches involves getting energy from the generating element to the system that needs the power. This is especially relevant for shoes, as it's hard to envision many practical appliances there (although it may be an appropriate location for a personal server without a local UI). Future possibilities include wires embedded into clothing or moving batteries from the shoe to the device after recharging [18], but these inconveniences compete with the relative ease of recharging from a power line connection when at home or in the office. Granted, this practice can become more complex as the number of wearable devices increases, but longer device lifetimes attained through clever power management and lower power electronics reduces the recharging frequency and the act of recharging may become more convenient if cordless inductive chargers become more established and accepted (e.g., [19,20]).

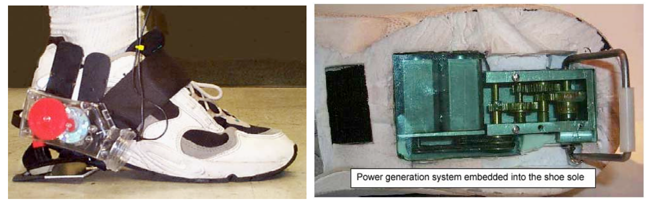

Figure 4: Magnetic generators grafted onto shoes as a strap-on test rig (left) and embedded into the shoe sole (right).

Figure 5: A pair of sneakers equipped with piezoelectric power-generating insoles and self-powered transmitter.

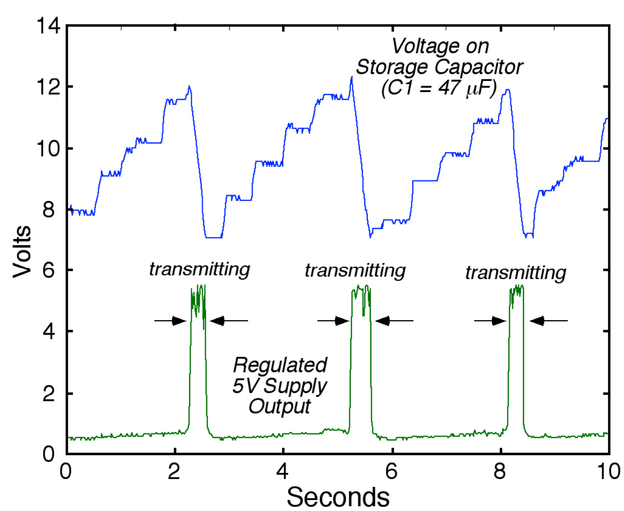

Figure 6: Waveforms produced when walking with the shoe in Fig. 5, showing voltage building on storage capacitor and transmission of the radio ID when enough power is stored.

Figure 7: An Active Parastic Mobility Node, detecting a proximate host (top) then launching and grappling onto their cuff (bottom).

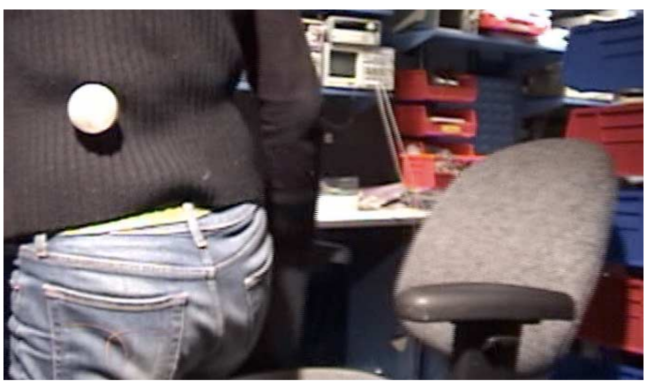

Figure 8: A sticky Passive Parasitic Mobility Node coated with silicone adhesive, having just transferred to the user's sweater from the chair back.

5. PARASITIC MOBILITY

A frontier of sensor network research explores mobile sensor nets, where sensing assets can be repositioned to appropriately sample dynamic phenomena, patch a gappy network, or be recovered or recharged. Most researchers in this field tend to see mobile sensor nets as a version of collaborative robotics, where each sensor node is embedded into a carriage of some sort that can move and navigate. Robotic platforms often tend to be heavy and power hungry, however, hence energy issues become prime concerns. Unless the environment is particularly conducive (e.g., using large solar cells atop rovers on the Martian surface), the opportunities for energy harvesting in mobile platforms can be limited. On the other hand, this is perhaps asking the wrong question – the goal here isn't necessarily to harvest large amounts of raw energy, but perhaps rather to harvest mobility.

We have started a program to explore this area, which we term "parasitic mobility" [21], by interpreting energy harvesting for mobile sensor networks as an adaptation of "phoresis" in nature, where nodes can actively piggyback on a proximate moving host (like a flea – Fig. 7), passively adhere to a host that comes into contact (like a burr – Fig. 8 – quasipassive nodes can shake off when they want to leave the host), or provide a symbiotic attraction to a passing host that makes them want to carry the sensor package (e.g., by attaching it to something useful yet disposable, like a pen – Fig. 9). Although parasitic nodes can be very lightweight, since the nodes only need sufficient energy and agility to attach to a nearby host and determine where it is bringing them, our existing prototypes (sized on the order of a 3 cm cube) are scaled more for vehicles rather than animate carriers – a situation that will change as the nodes grow smaller.

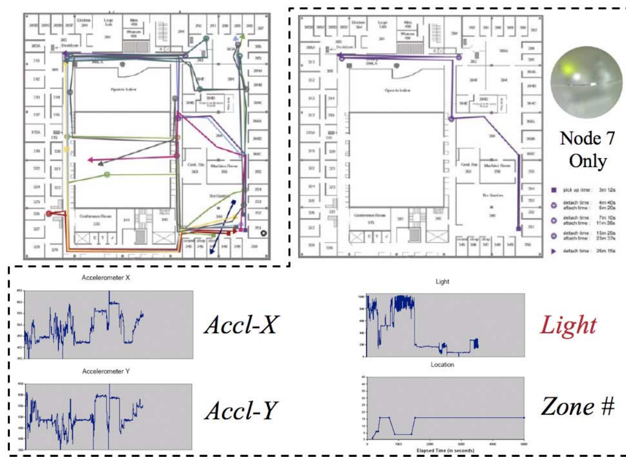

Figure 9: Tests of Symbotic Parasitic Mobility Nodes, which users were encouraged to pick up when seen, but put down when they flash and buzz. The nodes were zoned within a distributed Bluetooth network, and all had different goals (all node trajectories are shown at left). Although some were lost (e.g., locked into an office), most eventually attained their goals. The map at right and plots at the bottom show the trajectory of a node that wanted to be near bright areas – even though the accelerometers indicated that it had been put down and picked up repeatedly, it stayed in a region of the building where light was plentiful (lower values on the light plot indicate more light).

6. AMBIENT ENERGY RESERVOIRS

Rather than rely on garnering excess energy expended by the host human, another approach to wearable energy scavenging could be to tap into energy sources present in the environment at large. The most obvious of these is optical energy converted by wearable solar cells. A practical implementation of this approach needs both sufficient light and surface area to be available. Garden-variety polycrystalline solar cells tend to produce on the order of 100 mW/cm^2 when directed toward bright sun and 10-100 µW/cm^2 in a typically illuminated office. Certainly this is an attractive and well-mined option for bright environments. Mobile appliances in this niche include common solar-powered calculators and PDA's with solar cell cases [22]. As these devices tend to spend most of their time in the user's dark pocket, however, they have only limited access to light. Mounting solar cells on clothing is feasible, and has been often done. The best locations are generally atop the shoulders or head, where good access to light tends to be located – indeed, solar powered hats that drive fans or Peltier coolers date back a while (e.g., H.W. Dahly, US Patent # 3353191 from 1965). Indoor applications produce markedly less energy, although efficient low-power or low duty cycle applications are still possible (e.g., Citizen's Eco-Drive watch is powered by a solar cell hidden beneath a translucent dial and a recent data-logging pager badge made by Hitachi Research is powered by a small solar cell, 54 mm x 50 mm in area, mounted beneath the faceplate where it typically produced 70uA at 3V [23]). Although adaptive charging, load balancing, and dynamic impedance matching are well established in the solar power community, sensor network researchers have been recently adopting these techniques for increasing the longevity of solar-powered nodes [24,25]. Solar cell fibers currently under development hint at someday evolving flexible solar cell fabrics that can better integrate into clothing [26].

The increasing sources of RF pervading inhabited environments are often proposed as power sources. Typical energy densities, however, are generally much too low for practical personal scavenging with the limited antenna area available on a wearable device [27]. Conversely, small amounts of energy can be actively beamed at a user, dating back to Tesla and now commonly manifest as RFID. Implantable passive tags are not uncommon for ID'ing infants and animals, and implantable passive sensor tags (e.g., to remotely measure *in vivo* blood pressure) are now emerging from the laboratory [28]. Research by Mickle and collaborators at the University of Pittsburg works to produce a highly resonant regenerative antenna with an effective cross section that is much larger than its geometric area (perhaps by a factor of 1000 or more), potentially enabling milliwatt of energy extraction across a narrow RF frequency band from a very small physical footprint [29].

7. ADAPTIVE POWER MANAGEMENT

Most small wireless sensor nodes that run off scavenged power or an onboard battery need to be extremely miserly about consuming energy. With the exception of deployments that tap into heel strike, the motion of a heavy mass like a backpack, or a large-area solar array in bright light, wearable power sources siphoned from human activity tend to provide under a milliwatt. Although the semiconductor and computer architecture communities are very actively pursuing a broad agenda aimed at lowering the power needed for sensing and processing (e.g., variable voltage and clock rate scaling, large VLSI feature sizes to minimize leakage current, asynchronous and reversible/adiabatic processors, hybrid analog and digital signal processing, etc.), the bottom line in limiting sensor node power is to keep everything in deep sleep and powered off as much as possible.

Today's commercial micropower analog operational amplifiers enable simple analog sensor processing for under a few microwatts, and nanopower comparitors enable digital discrimination of analog signals for less than a microwatt. Exploiting these advances, we have built a family of devices that exploit what we term "QuasiPassive Wakeup," allowing a node to become activated directly by analog sensor stimuli conditioned from passive or ultra-low-power active filtering. These have included extremely simple "featherweight" nodes that wake up from vibration [30] and micropower optical RFID tags [31].

While Moore's Law has enabled us to design and deploy highly compact multisensor platforms that provide a rich description of phenomena via several different flavors of measurement, extending the life of the correspondingly shrinking battery or energy source mandates that all sensors can't be continually powered, but must rather spend most of their time sleeping or turned off. Accordingly, we are developing an automated framework that we term "Groggy Wakeup" [32] where, by exposing an analysis to labeled data from particular phenomena to be detected and general background, we evolve a power-efficient sequence of hierarchical states, each of which requires a minimal set of activated sensors and calculated features, that ease the system into full wakeup. Accordingly, the sensor system only comes full on when an appropriate stimulus is encountered, and resources are appropriately conserved – sensor diversity is leveraged to detect target states with minimal power consumption, and once the detection is achieved, all sensors are activated to measure, log, or process the phenomena in detail. Although our initial development targets wearable platforms seeking to detect and measure medically relevant phenomena [33], the Groggy Wakeup framework will be applicable to many applications of embedded sensing.

8. CONCLUSIONS

This paper has surveyed a broad spectrum of approaches to energy harvesting for portable and wearable electronics. Solar energy collection (if the light is there), tapping into heel strike, and exploiting reaction forces against a heavy load like a backpack have been demonstrated to provide up to several watts of power for ambulatory users, as does direct manipulation by cranking, pedaling, pulling, etc. Most other wearable parasitic sources, however, provide a much leaner harvest before annoying the user, gleaning between milliwatts and microwatts. Although the idea of powering electronics parasitically from human motion is attractive, realistic markets may be limited to particular niches (e.g., hikers or military users), as the low power systems compete with embedded batteries coupled with efficient power management (note that self-winding electric watches have become boutique items since watch batteries now last for many years) and higher-yield systems grapple with aesthetic practicality (e.g., generators on the shoe or solar cells on the head), the issue of transporting energy to places where it is needed, and the relative convenience of occasionally recharging mobile appliances from a power line. That said, the idea of building portable electronic devices that never require charging or battery replacement has the attraction of perpetual motion machines, and in some cases (e.g., implantable electronics or distributed micropower sensors for medical monitoring) become highly relevant, hence development will continue, and the future may hold radical reinterpretations of a more generic concept of "harvesting" that our parasitic mobility systems only begin to hint at.

9. ACKNOWLEDGMENTS

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