Acoustic power management by swarms of microscopic robots

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Abstract
Microscopic robots in the body could harvest energy from ultrasound to provide on-board control of autonomous behaviors such as measuring and communicating diagnostic information and precisely delivering drugs. This paper evaluates the acoustic power available to micron-size robots that collect energy using pistons. Acoustic attenuation and viscous drag on the pistons are the major limitations on the available power. Frequencies around 100kHz can deliver hundreds of picowatts to a robot in low-attenuation tissue within about 10cm of transducers on the skin, but much less in high-attenuation tissue such as a lung. However, applications of microscopic robots could involve such large numbers that the robots significantly increase attenuation, thereby reducing power for robots deep in the body. This paper describes how robots can collectively manage where and when they harvest energy to mitigate this attenuation so that a swarm of a few hundred billion robots can provide tens of picowatts to each robot, on average.

Keywords Acoustic power · Implanted medical devices · Swarm energy allocation · Distributed control

1 Introduction

As implanted medical devices become smaller, more numerous and more capable, they will enable many high-precision applications [1–4]. In particular, microscopic robots have the potential to provide precise treatments throughout the body on the scale of individual cells. A significant challenge for realizing this possibility is providing power to the robots [5, 6]. Among the options for powering such robots [7–10], ultrasound has some appealing advantages. These include noninvasive power from transducers on the skin without requiring tethers to the robots, readily available ultrasonic transducers in clinical settings, and the ability to direct power to specific locations in the body. In addition to delivering energy, ultrasound can aid robots’ tasks by altering their local environments, such as selectively opening the blood-brain barrier for drug delivery [11, 12].

One approach to acoustic power creates structured fields that apply forces to objects in the body to move them in specific directions [13]. This capability extends to microscopic robots [14–16], such as micron-size particles in the bloodstream [17]. For example, sound can generate oscillations in bubbles embedded in robots to propel them [18–20]. In these cases, ultrasound provides both power and control of robot behavior. These uses of ultrasound to exert forces on objects in the body contrast with using ultrasound to create images based on variation in tissue acoustic properties.

More complex microscopic robots could behave autonomously by using on-board logic to respond to their local environments [21]. These robots could include pumps to collect or release chemicals, motors to move flagella for locomotion or vibrate the robot’s surface for acoustic communication, or springs for energy storage.

Using their internal controllers, autonomous robots determine when and how to use harvested energy, e.g., for locomotion, communication or drug release. These decisions can account for sensed data, information received from neighboring robots, and the history of such information as recorded in the robot’s memory. Even relatively simple on-board control can provide a wide range of customized behaviors [22]. For example, nearby robots could release drugs simultaneously at a microscopic target location they identify with their sensors [23]. This would produce a large sudden increase in drug concentration at that location.

In addition to power, ultrasound can provide high-resolution functional imaging [24] and commands to the robots by modulating the acoustic wave. This imaging could monitor...
the robots on scales considerably larger than an individual robot and guide robots to macroscopic target areas within the body. For example, acoustic power and activation commands could be directed toward those target areas once imaging determines a sufficient number of robots have arrived in the area. A robot could combine these external signals with those communicated from its neighbors to provide larger-scale context to that robot’s sensor measurements. This combination of information from multiple scales shared among the robots could increase the precision and coordination of the robots.

Of particular interest for medicine is the eventual development of autonomous robots a few microns in size. These are the largest robots that can travel throughout the circulatory system, whose capillaries are several microns in diameter [8]. By accessing the full circulatory system, such robots could pass as close as blood does to cells throughout the body. Specifically, to provide nutrients to cells and remove their waste products, capillaries carry blood within tens of microns of cells, which is close enough to allow rapid chemical exchange between the blood and the cells via diffusion [25]. Thus injecting the robots into the blood allows them to reach locations close to cells in microenvironments whose sensed properties match the robot task requirements.

Micron-size robots are considerably smaller than sub-millimeter micromachines [21] based on microelectromechanical systems (MEMS) which are too large to travel through capillaries. On the other hand, they are much larger than nanoparticles used for drug delivery, which can only incorporate a few logic operations to autonomously determine their behaviors [26]. Theoretical studies suggest micron-size robots are large enough to have sufficient computation, sensing and communication to coordinate complex activities with single-cell resolution [8, 10, 27–29]. Thus this size range could provide a useful combination of robot capability and access to cells via the body’s circulatory system.

Microscopic robot applications can involve large numbers of robots. For instance, micron-size robots could provide customized medical diagnostics and treatments to individual cells throughout the body [30]. This task requires a correspondingly large number of robots to provide a reasonable treatment time, e.g., a few hours. Thus the scenarios discussed in this paper consist of billions of robots, with a total mass in the range of tens to hundreds of milligrams [8].

Interactions among robots can create swarms with performance and robustness beyond that of individual robots [31], including a variety of coherent structures and behaviors [32]. For microscopic robots, external fields can induce these interactions from forces on the robots [14] to form, for instance, specific shapes [33] and fluid motions [34, 35]. For more flexibility, interactions among autonomous robots can arise from their controllers coordinating with neighbors by exchanging information [36, 37].

With respect to acoustic power, a swarm can consist of so many robots that they significantly alter sound propagation in tissue. In particular, robots absorbing acoustic energy increase attenuation of the sound passing through tissue containing the robots. This attenuation can be much larger than that due to the tissue, even if the robots, in total, occupy a relatively small fraction of the tissue volume. In this case, the swarm becomes the main determinant of acoustic energy propagation. Thus instead of a fixed attenuation determined by the tissue, robots that dominate the attenuation have an opportunity to improve task performance by coordinating their behaviors so as to adjust the amount and location of acoustic power.

To quantify how large numbers of microscopic robots affect acoustic power, this paper considers micron-size robots that absorb energy to power internal mechanisms. Ultrasound power often uses piezoelectric energy harvesters [38]. An alternative, and the focus of this paper, is mechanical energy harvesting [39]. Mechanical harvesters avoid the need to distribute electricity within the robot, possibly with large resistive losses, and mechanisms to convert electricity to mechanical motion needed to actuate machines on the robot surface, e.g., for locomotion [40, 41], or within the robot, e.g., mechanical computers [42, 43]. Specifically, this paper considers spherical robots that harvest energy with pistons on their surfaces, as illustrated in Fig. 1. In addition to pistons shown in the figure, the robot contains machines that utilize the collected energy, including control and communication to allow coordinating with other robots. Aside from the pistons, the robots are taken to be stiff structures with negligible response to the acoustic pressures considered here.

Using typical acoustic properties of tissue, this paper evaluates the power available to a single robot, and applies that result to determine the power available to a swarm of these robots. Thus, in contrast to evaluating power for only one or a few microscopic robots, this paper quantifies how billions of robots distributed throughout the body affect the available power, and how these robots can collectively mitigate those effects by coordinating their activities.

2 Methods

The effectiveness of mechanical energy harvesters is limited by their material properties, such as stiffness and friction drag coefficient. To estimate the ultimate potential of ultrasound power for microscopic robots, this paper considers harvesters consisting of materials whose properties are close to theoretical limits [44] of atomically precise manufacturing [45, 46], and which have been studied in the context of microscopic robots [1].
The main factors determining the power available to a robot are the acoustic pressure at the robot’s location and how effectively the robot can extract power from that pressure variation.

Acoustic pressure at the robot depends on its distance from transducers on the skin and how sound propagates through the body [47]. The main factor considered here is attenuation, the conversion of sound into heat as it propagates. Specifically, this paper considers robots in tissue with representative acoustic properties given in Table 1 and the range of frequencies shown in Table 2. The sound wavelength is considerably larger than the robots, so the sound pressure at a given time is the same everywhere on the robot’s surface. This property simplifies the evaluation of robot power and how the robots scatter the sound.

For these frequencies, acoustic attenuation in tissue is proportional to frequency and is conveniently quantified by the amplitude absorption coefficient $\alpha_{\text{tissue}}$, given in Table 1 for representative low- and high-absorption tissues [8]. Acoustic pressure of frequency $f$ decreases by a factor of $\exp(-\alpha_{\text{tissue}}xf)$ over a distance $x$.

A robot can extract acoustic energy with components that move in response to acoustic pressure variations at its location. This study considers the motion of pistons on the robot surface. At these sizes, viscosity of the fluid surrounding the robot is the dominant source of drag on the pistons. The size of this drag determines the power a piston can deliver as a function of its area and range of motion when subjected to sound of a specified frequency and pressure amplitude.

Since ambient pressure varies throughout the body, e.g., between arteries and veins in the circulation, the restoring force for these pistons must adjust to compensate for these changes as robots move around the body. Otherwise pistons will often be pinned at one extreme of their range of motion and not provide power. To avoid this loss of power, pistons include adjustable springs that compensate for ambient pressure variation.

The primary focus of this paper is on how a swarm of robots alters the sound waves, and thereby the power available to robots in the body. This effect arises from combining the energy removed from the sound wave by many robots, accounting for how individual robot energy harvesting varies with pressure and hence depth in the body. While a single robot has negligible effect on the sound wave, the energy absorbed by large numbers of robots can significantly increase the attenuation, well beyond that of biological tissue. In this case, acoustic energy propagation is determined mainly by the swarm of robots rather than the tissue attenuation. The reduction in sound pressure due to this attenuation alters the amount of energy robots remove from the sound.

![Schematic illustration of the microscopic robots considered in this paper, which use pistons to collect acoustic energy. (a) robot with fully retracted pistons. (b) robot with transparent surface to show the pistons and their housings within the robot. The example used to illustrate the power available to the robots has a diameter of two microns with piston dimensions given in Online Resource 1](image)
wave and hence how much they attenuate the sound. This paper combines these effects to evaluate power availability and distribution among large numbers of robots. Online Resource 1 provides details of this evaluation.

3 Results

This section describes the acoustic power available to a single robot at various distances from the skin, the additional attenuation due to large numbers of such robots, and behaviors robots could use to mitigate that additional attenuation.

3.1 Acoustic power for a robot

At high frequencies or low pressures, the power provided by a piston is proportional to the square of the acoustic pressure and the piston’s surface area, but is independent of acoustic frequency. In this case, the piston oscillates without ever reaching the limits of its motion. At low frequencies or high pressures, power is linearly proportional to pressure, frequency and the displacement volume of the piston. In this case, the piston can be pinned at a limit of its motion for a portion of the acoustic oscillation. An animation (Online Resource 2) provides an example of how pistons move in response to acoustic pressure.

For example, a piston in a robot next to the skin in the scenario described in Table 3, receives 50 kPa of acoustic pressure. At 100 kHz and 200 kHz, the piston moves through its full 200 nm range of motion and provides 84 pW and 115 pW, respectively. At 300 kHz and 500 kHz the piston delivers 116 pW, independent of the frequency, while moving through 140 nm and 83 nm, respectively. Larger distances from the skin provide less pressure due to attenuation, as indicated in Table 1. For instance, in soft tissue 20 cm from the skin, 500 kHz has pressure reduced to 22 kPa and the piston provides 22 pW while moving through 36 nm. The total power available to the robot is these power values for one piston multiplied by the number of pistons the robot contains.

These observations indicate a trade-off in the choice of frequency. The increasing attenuation with frequency favors using lower frequencies, which better propagate through the body. However, pistons are less effective energy harvesters at lower frequencies. These relationships identify suitable choices of acoustic frequency and piston parameters to effectively deliver power to robots depending on tissue type and distance from transducers on the skin.

To illustrate this trade-off, we consider the scenario in Table 3. The robot uses multiple pistons to extract power. The duty cycle given in the table could arise from a robot occasionally turning off power collection to enable (or simplify the design or control of) other uses for its surface that are affected by piston motions. Or the duty cycle could arise from a swarm mitigation technique discussed below.

Safety limits ultrasound intensity to about 1000 W/m² for extended use [48], which corresponds to pressure amplitude p=55 kPa. For transducers well-coupled to the skin over soft tissues, reflection losses can be fairly low, e.g., 10%. These values provide the acoustic source parameters in Table 3.

Two robot placements illustrate the available power: in soft tissue and in a lung (see Table 1). The lung surface is about 5 cm beneath the skin, leading to some attenuation between the transducer on the skin and the surface of the lung. Furthermore, the different acoustic impedances of lung and soft tissue means only about 36% of the acoustic energy reaching the lung is transmitted into it [8]. The power reaching various parts of the lung depends on their locations relative to the ribs and transducers on the skin [47]. An approximate accounting for these factors estimates acoustic energy for the lung as first attenuating through 5 cm of soft tissue, after which 20% of the incident energy enters the lung.

With these estimates, Fig. 2 shows power available to a robot at various depths in soft tissue and in a lung, with the acoustic source described in Table 3. The maximum power occurs near the largest frequency with sufficient pressure to move the pistons through their entire range of motion. At lower frequencies, the pistons move more slowly, resulting in less power. At higher frequencies, the reduced pressure due to increased attenuation results in slower motion and pistons do not move over their full range, also resulting in less power. Thus the power-maximizing frequency arises from simultaneously maximizing the speed and range of piston motion.

The figure indicates that frequencies around 100 kHz are best for powering robots in regions with low attenuation between the robot and the sound source. Lower frequencies, e.g., 40 kHz, are better for robots in a lung, but robots deep in a lung have much less power. As a point of comparison,
a human cell uses about 100 pW, though with considerable variation among cell types and activity levels [8, 49].

### 3.2 Sound attenuation by a swarm of robots

Prior studies of powering microscopic robots focus on well-separated individual robots or a few nearby robots [7–9, 50]. However, proposed applications involve large numbers of robots [8, 29], which could significantly attenuate sound, analogous to the increased attenuation due to bubbles [51]. Thus accessing the applicability of acoustic power to swarms of microscopic robots requires estimating how large numbers affect sound propagation, as described in Online Resource 1. This section describes attenuation due to many robots for the scenarios in Table 4.

As an example, Fig. 3 shows how $10^{11}$ robots affect available power in soft tissue and a lung. Comparing with Fig. 2 shows that this many robots leads to significant power reductions in soft tissue at the higher frequencies and distances. However, the robots add a relatively minor amount to the lung’s large attenuation. Attenuation increases with additional robots and thereby results in less available power, as shown in Fig. 4 for robots in soft tissue.

For the scenario of Fig. 3, averaging over locations in the body, $10^{11}$ robots each have around 100 pW, so the robots, in total, collect tens of watts. In this example, transducers deliver 1000 W/m$^2$ over much of the body’s surface, so the total power is about 1000 W. Robots extract only a small portion of this total.

### 3.3 Compensating for swarm attenuation

A swarm of microscopic robots significantly increases attenuation in tissue. Unlike passive particles, microscopic robots can coordinate their behavior [27] to mitigate this attenuation based on robots’ task requirements in their local environments. This section describes and evaluates several mitigation strategies robots could use individually or in combination, possibly at different times or locations.

#### 3.3.1 Limiting robot power collection

Acoustic attenuation produces a highly nonuniform distribution of power in the body. Robots absorbing power increase attenuation and thus increase this variation. This means robots near the skin have a great deal of power, while those deeper in the body have little.

Robots near the skin could reduce this power gradient by limiting their power collection, e.g., by locking some pistons in place. Alternatively, a robot could reduce the power collected by each piston. This could involve slower motion (by increasing the load on each piston) or stopping pistons during a portion of each acoustic cycle (e.g., by reducing the range of piston motion). For the same power, the latter approach leads to more dissipation, and hence higher attenuation. Thus slowing piston speed is the better option.

Stopping piston motion over several acoustic cycles rather than just part of one has an additional benefit if robots near the skin synchronize their duty cycles for absorbing power: while all robots near the skin stop absorbing power, they reduce sound attenuation, making bursts of higher power available to deeper robots. This contrasts with unsynchronized duty cycles, which only somewhat increases average power to deeper robots. A synchronization signal could be added to the sound wave from transducers, or could be provided from clocks in the robots.

Another option is to select the range of pistons so that high pressure variation pushes them to their limits. This is particularly useful for robots intended to operate near the skin. Such robots can get significant power without a large range for pistons and will have more of their volume available for other uses.

Collecting less power reduces the major contribution to acoustic attenuation even though these robots still attenuate sound through dissipation in a boundary layer at their surface and by scattering (Online Resource 1). As an example

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**Table 4** Scenarios with various numbers of robots in a body with volume $V_{body} = 50L$. The typical spacing is the average distance between neighboring robots, estimated as the cube root of the average volume per robot.

| Number | Typical spacing | Number density |
|--------|-----------------|----------------|
| $10^{10}$ | 170 $\mu$m | $2 \times 10^{11}/m^3$ |
| $10^{11}$ | 80 $\mu$m | $2 \times 10^{12}/m^3$ |
| $10^{12}$ | 40 $\mu$m | $2 \times 10^{13}/m^3$ |
of this strategy, Fig. 5 shows a situation with such a large number of robots that little power remains 20 cm from the source (see Fig. 4). In this case, robots that limit their power considerably increase the depth at which other robots receive substantial power.

### 3.3.2 Using multiple frequencies

Using two or more frequencies can provide more power to robots deeper in the body. With this approach, robots near the skin extract power from a higher frequency, while a lower frequency, with lower attenuation, is reserved for deeper robots. A limitation of this approach is that the combined intensity of the frequencies must not exceed the safe limit on total intensity. Thus splitting the sound among two or more frequencies means less power from each frequency than if using that frequency alone.

Figure 6 is an example of this strategy. Robots monitor the power available from the higher frequency, and use that frequency for power when it provides at least 2.3 pW, which occurs at a distance of 8 cm from the source. Otherwise they switch to the lower frequency. In this case, robots 10 cm from the source have more power than those a bit closer to the skin. This split-frequency approach provides significantly more power to deeper robots than when all robots use just one of these frequencies.

### 3.3.3 Positioning robots to provide low-attenuation paths

Robots avoiding locations between skin and a region of deeper tissue can allow more sound to reach robots in that deeper region. With this method of sharing acoustic power, robots manage energy collection and use as a group, rather than each robot focusing only on its own energy requirements. This approach is especially useful if the main power-using activities are in relatively small, deep regions of the body. The animation (Online Resource 3) illustrates this approach.

Figure 7 is an example of this strategy where robots avoid paths between transducers on the skin and the surface of the lung. In this case, the number of robots is large enough to considerably attenuate the sound in the tissue between the lung and the skin (see Fig. 4).

Generalizing from this example, methods that design swarm behaviors to form specific global shapes [52] and with specific collective behaviors [53] could be applied to produce desired patterns of acoustic waves. Combining...
these swarm design techniques with how robots affect acoustic waves could allow a swarm to adjust available power in ways suited for specific robot missions. For example, robots able to move independently and measure their distances to neighbors could position themselves to precisely tune acoustic properties at scales well below the wavelength, thereby creating dynamic acoustic metamaterials [54].

### 3.3.4 Heterogeneous robots

The examples of available power in this paper use the scenario of Table 3. More generally, a swarm could consist of robots with different designs, such as using different numbers or sizes of pistons. This heterogeneity can improve swarm performance when different types of robots are best suited for different tasks required for their overall mission [55].

For example, in some applications, robots may remain in one location for an extended period of time, e.g., to measure individual cells throughout the cell cycle. This task could benefit from different types of robots. E.g., robots designed to work in high-power environments near the skin could only use high frequencies and hence could have fewer, shallower pistons. Such pistons would not be as effective at collecting power from lower frequencies. On the other hand, robots intended for deeper operation could devote more of their volume to pistons to more efficiently collect power from lower frequencies. Thus, a heterogeneous mixture of robots could better match the availability of acoustic power than if all robots have the same design.

Different designs could be useful even if robots continually change their distance from the skin, e.g., as they move with blood in the circulation. In this case, robots could usually operate with a small baseline power for their controller, possibly from stored energy. Then, when they find themselves in an environment suited to their design, they could activate their full operation. Due to the large number of robots in the swarm, this intermittent activation can still have many activated robots at all times.

### 4 Discussion

This paper evaluated ultrasonic power for swarms of microscopic robots using mechanical energy harvesters. Frequencies around 100 kHz provide the most power in much of the body. When the number of robots in the body exceeds about a hundred billion (corresponding to a total mass of a few tenths of a gram), the robots significantly increase acoustic attenuation, thereby reducing the power available to robots deep in the body. Similar attenuation can occur locally, e.g., in a single organ, with fewer robots that concentrate at those

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Fig. 6 Power with $10^{12}$ robots. The solid curves show power for the scenario of Table 3, except the 1000 W/m$^2$ source intensity is split between 100 kHz and 300 kHz, with source pressures 43 kPa and 23 kPa, respectively. Robots use the higher frequency at small depths and the lower frequency at large depths. The dashed curves show power available when all robots extract power from just one of the frequencies, each with intensity of 1000 W/m$^2$.

Fig. 7 Power for robots in a lung when there are $10^{12}$ robots in the body for the scenario of Table 3. The solid curves are when robots avoid locations between the lung surface and the skin. The dashed curves are when robots absorb power at all locations. The values next to the curves indicate distances from the skin-facing surface of the lung.
locations. This reduction would not be apparent in experiments involving a small number of robots. Thus a method to power implanted devices that is adequate for a few robots could fail when applied to large numbers. In such situations, designing missions for microscopic robots must account for their collective effects. Robots with relatively modest sensing, communication and computation capabilities can mitigate this attenuation with swarm behaviors such as those discussed in this paper and illustrated in Fig. 8. These behaviors can flexibly deliver power to robots where and when that is most important for their medical task.

The results of this paper can help identify applications of swarms of microscopic robots where acoustic power is a good option. Since the total collected power is the product of the number of pistons on the robot and the power collected by each one, the power evaluated here for spherical robots also applies to other shapes that contain the same pistons, providing flexibility in selecting the robot shape. These results can inform the design of such robots when they become feasible to manufacture in large numbers. Conversely, the mitigating swarm behaviors discussed here can reduce the complexity, of both hardware and software, that each robot would need to operate in spite of the enhanced attenuation from other robots, e.g., by including sufficient onboard energy storage and associated control computations, in the absence of such mitigation. This could somewhat simplify the formidable challenge of manufacturing the microscopic robots considered here.

There are several directions for future study of acoustic power for swarms of microscopic robots. One direction is designing and building acoustic energy harvesters that best exploit the limited robot volume and surface area with the constraint of viscous drag on motion in the fluid around the robot. These energy harvesters must not only effectively extract energy from acoustic waves, but also ensure biocompatibility. For example, this requires minimizing the rate at which surrounding materials stick to the moving surfaces and inhibit their operation. Moreover, the immune reaction to small devices can depend on their shape as well as surface chemistry [56]. This biocompatibility requirements for the duration of the robots’ mission may constrain design choices for the number, size, range of motion and shape of the pistons.

Another direction is evaluating how large numbers of robots affect structured acoustic fields used to move robots [14–16], which are more complex than the long-wavelength plane waves considered here. Thus it will be important to evaluate changes to the field structure, and forces they can apply, in addition to overall attenuation of the field strength. If these robots also absorb energy for their internal use, using different frequencies for internal robot power and the structured fields would reduce competition among these uses of the sound. Nevertheless, such uses would still have dependencies due to safety limits on total acoustic intensity delivered to the body, similar to that seen for the dual-frequency approach shown in Fig. 6.

A third direction of study is more precisely evaluating available power in the complex acoustic environment of the body, including the effect of heterogeneous tissues, with varying acoustic properties [47]. Available power will also depend on the locations and activities of other robots, both nearby and between the robot and the acoustic sources on the skin. Thus it will be important to evaluate how the mitigating strategies described in this paper perform with the variation in tissue properties and how swarms can adapt to those variations to support a wide variety of high-precision medical applications.

**Fig. 8** Summary of a swarm of microscopic robots arranging for power to reach robots deeper in the body. From left to right, a single robot with pistons collects power from acoustic waves, a robot among blood cells, schematic of sound highly attenuated in the body due to absorption by many robots, and a region of robots near the skin avoiding power collection (open circles) to allow deeper robots (solid points) to receive more energy. The robots considered here are smaller and more numerous than indicated in this schematic diagram of multiple robots in tissue.
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Declarations

Conflict of interest The author has no conflicts of interest to declare that are relevant to the content of this article.

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