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Moyer et al.

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(54) **INGESTIBLE DEVICE WITH PROPULSION CAPABILITIES**

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A61B 1/04 (2006.01)
H04N 5/232 (2006.01)
(Continued)

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CPC ***A61B 1/041*** (2013.01); ***A61B 1/00006*** (2013.01); ***A61B 1/00009*** (2013.01); ***A61B 1/0011*** (2013.01); ***A61B 1/0016*** (2013.01); ***A61B 1/00016*** (2013.01); ***A61B 1/00032*** (2013.01); ***A61B 1/00036*** (2013.01); ***A61B 1/00156*** (2013.01); ***A61B 1/045*** (2013.01); ***A61B 1/06*** (2013.01); ***A61B 1/31*** (2013.01);
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See application file for complete search history.

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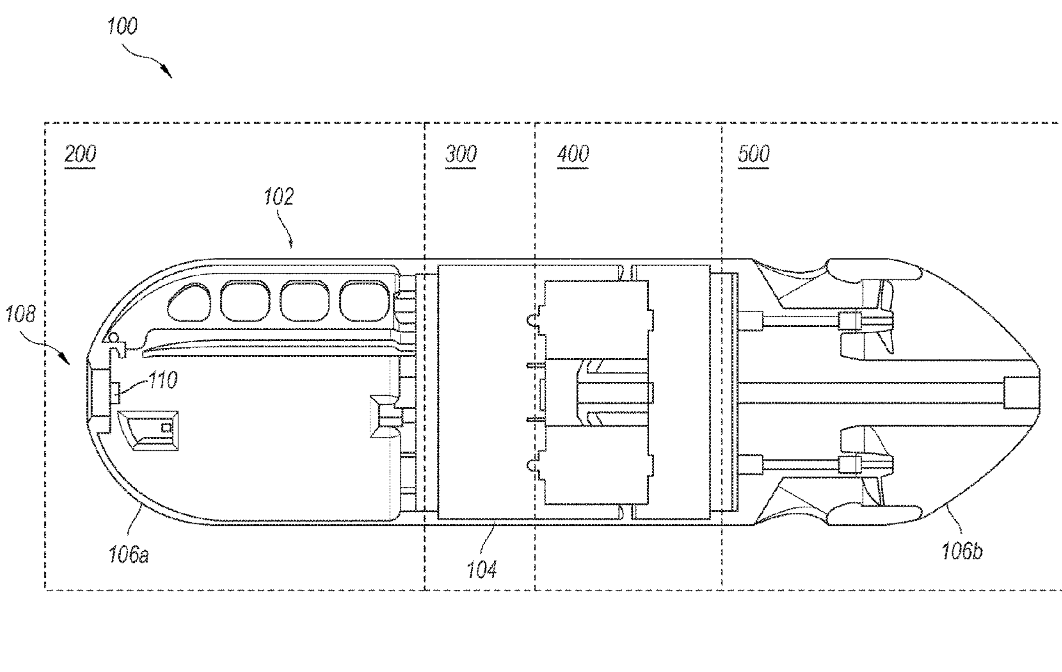
(57) **ABSTRACT**

Introduced here is an ingestible device comprising a capsule having a central axis therethrough, at least one propulsion component, and at least one motor configured to supply motive power to the propulsion component(s). The propulsion component(s) may be disposed at locations radially offset from the central axis. Upon receiving input indicative of a request to alter a position and/or an orientation of the ingestible device, the motor(s) can supply motive power to some or all of the propulsion component(s) to cause movement of the ingestible device.

12 Claims, 16 Drawing Sheets



(51) **Int. Cl.**

H01Q 7/00	(2006.01)
A61B 1/00	(2006.01)
A61B 10/04	(2006.01)
H04N 5/225	(2006.01)
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H04B 1/713	(2011.01)
H04N 5/40	(2006.01)
A61B 1/31	(2006.01)
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(52) **U.S. Cl.**

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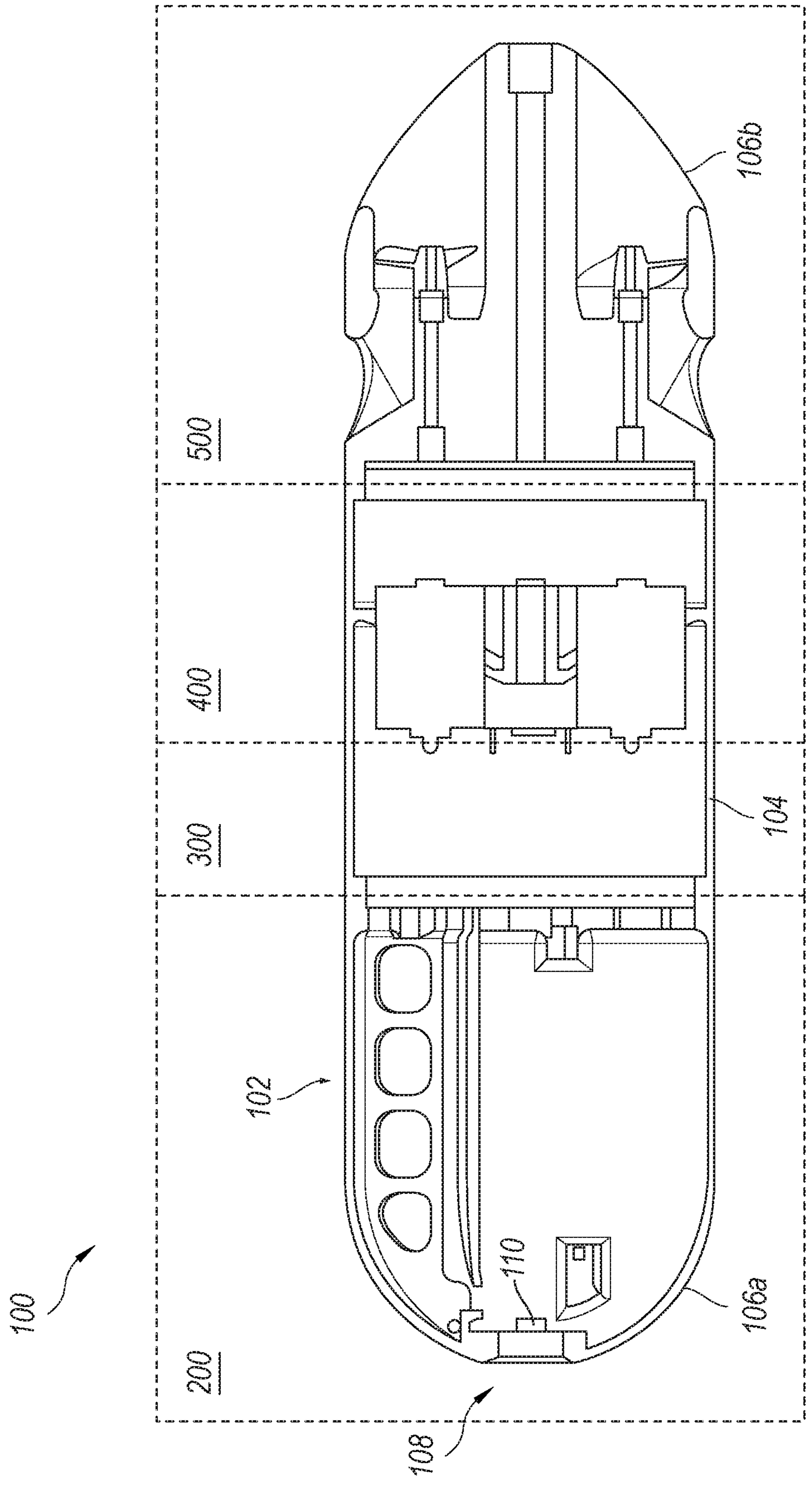

FIGURE 1

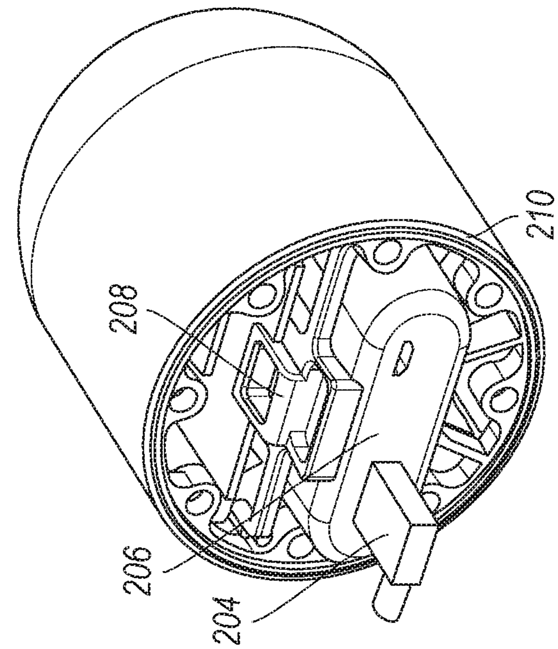

FIGURE 2B

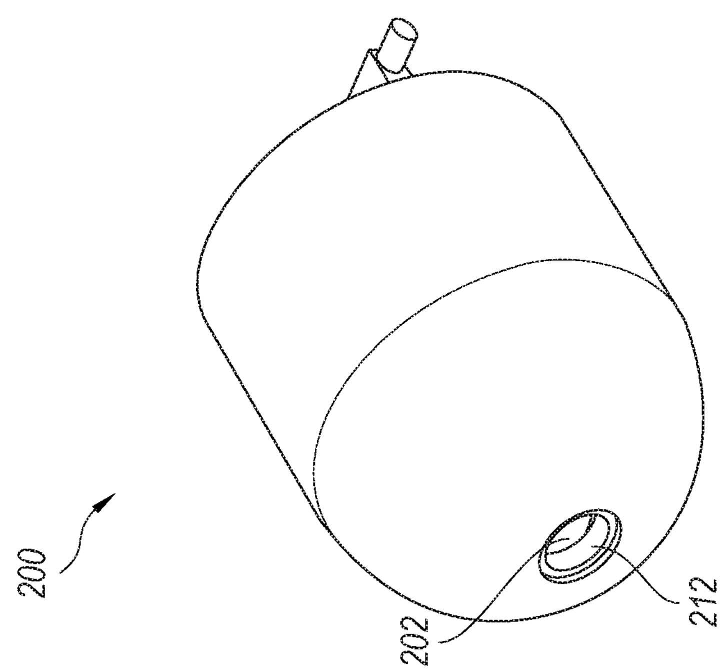

FIGURE 2A

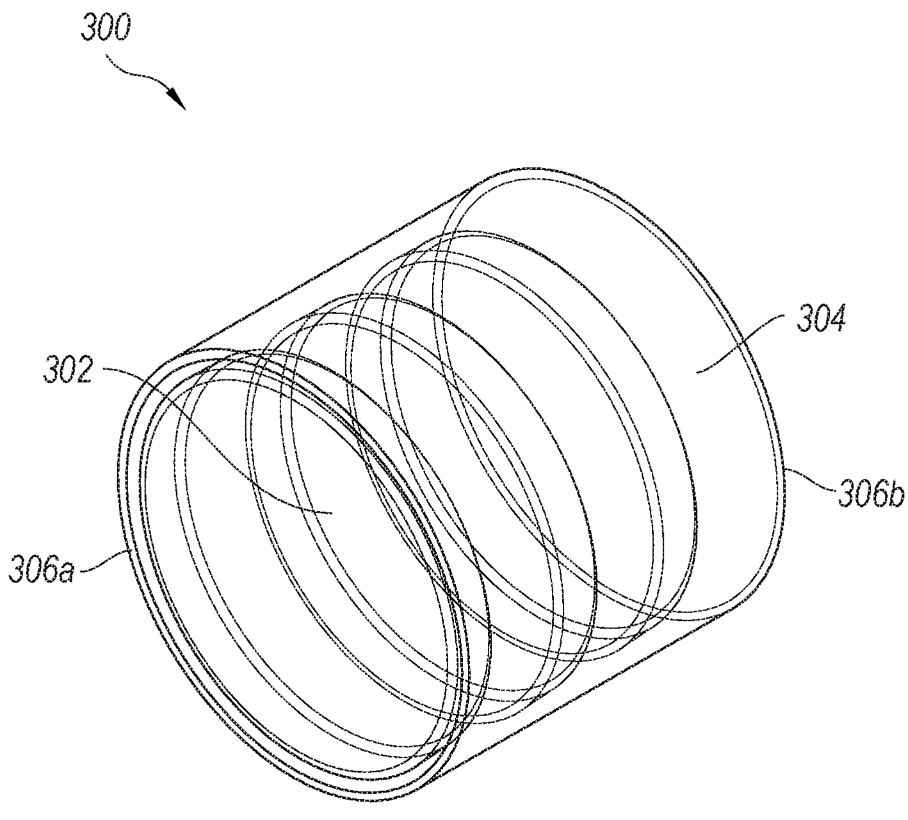

FIGURE 3

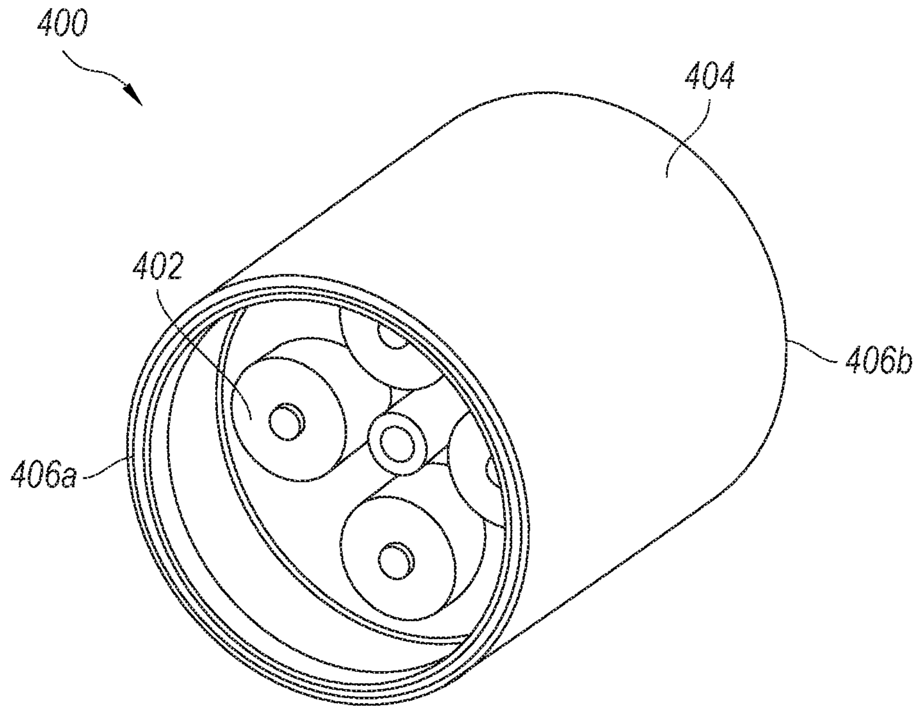

FIGURE 4

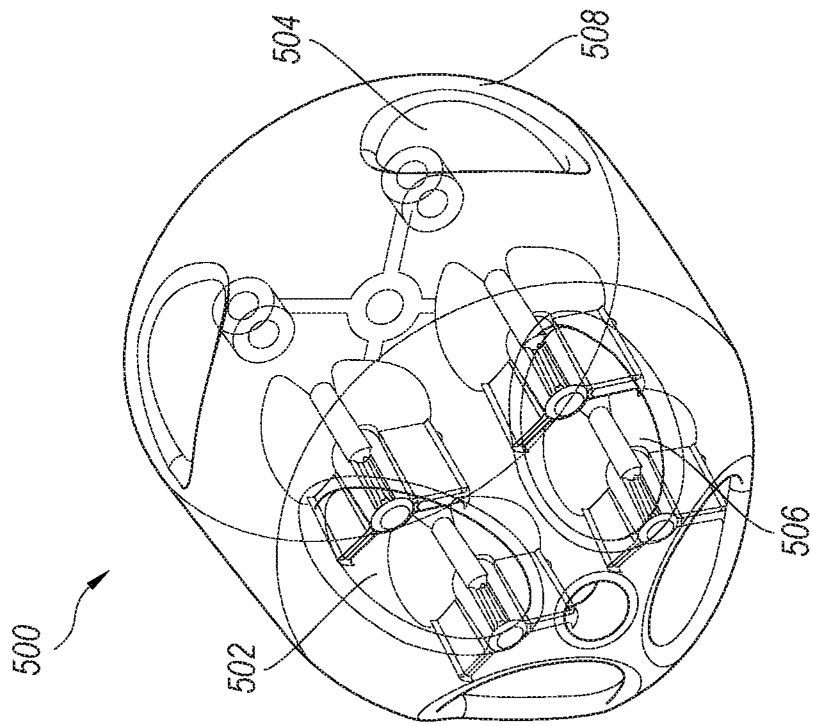

FIGURE 5B

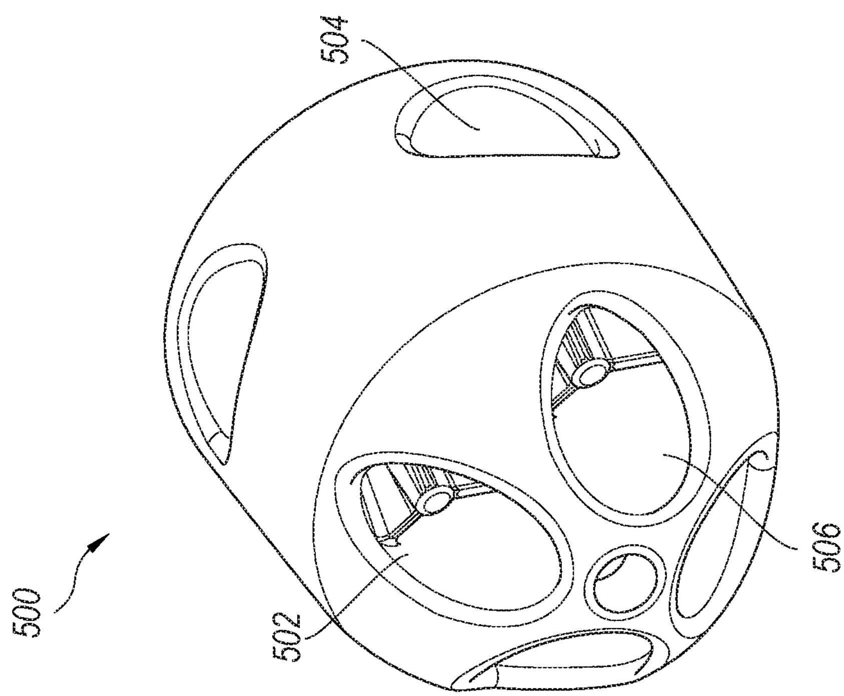

FIGURE 5A

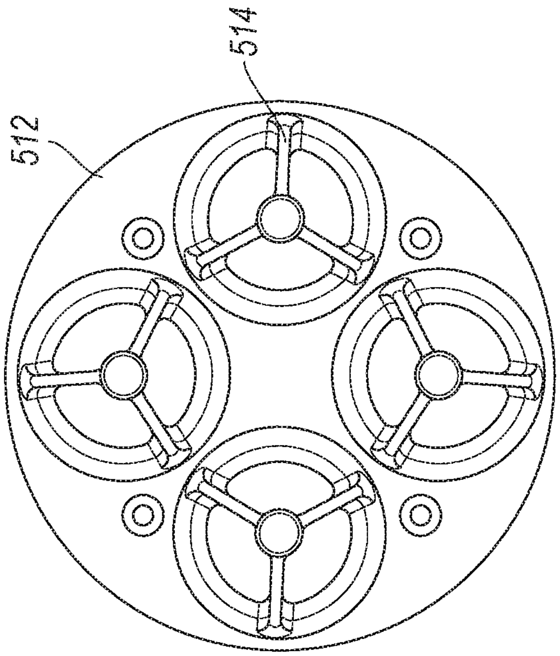

FIGURE 5D

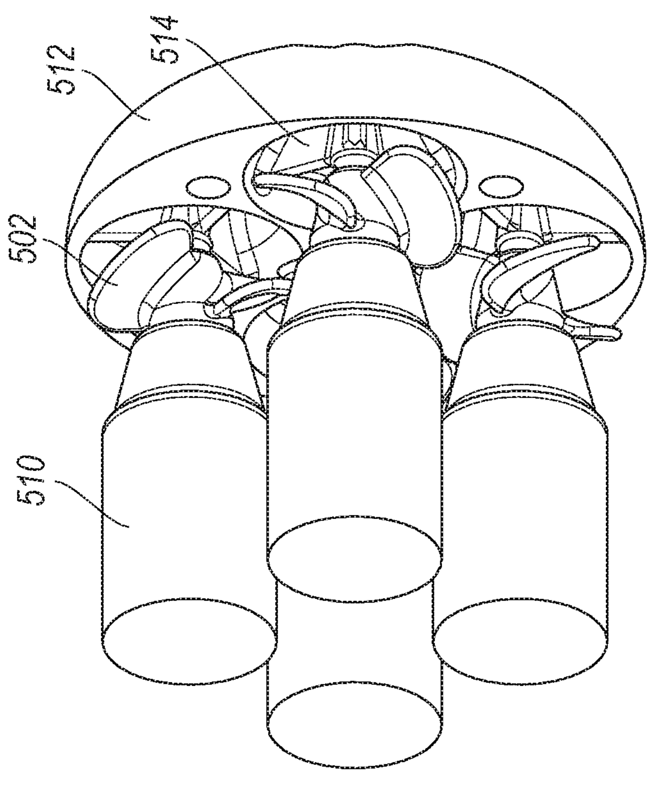

FIGURE 5C

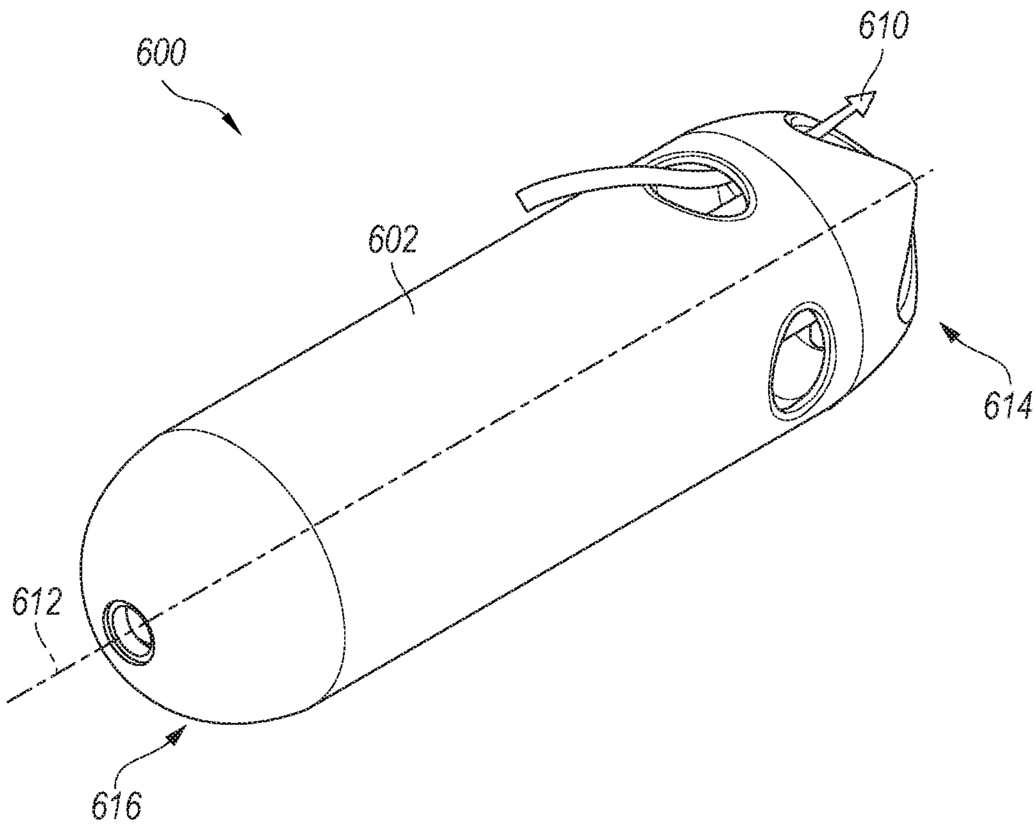

FIGURE 6A

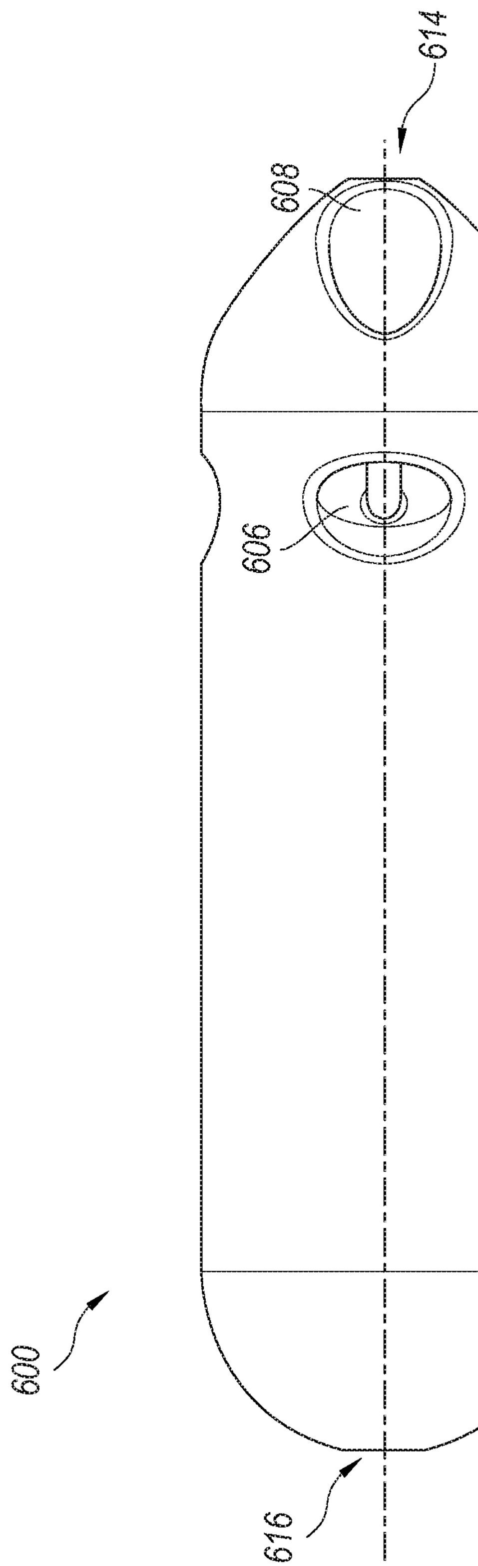

FIGURE 6B

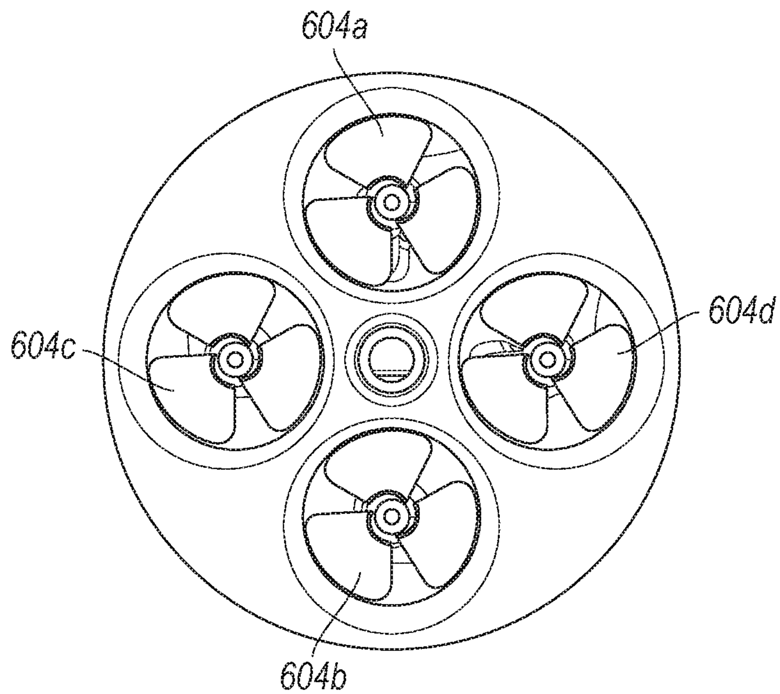

FIGURE 6C

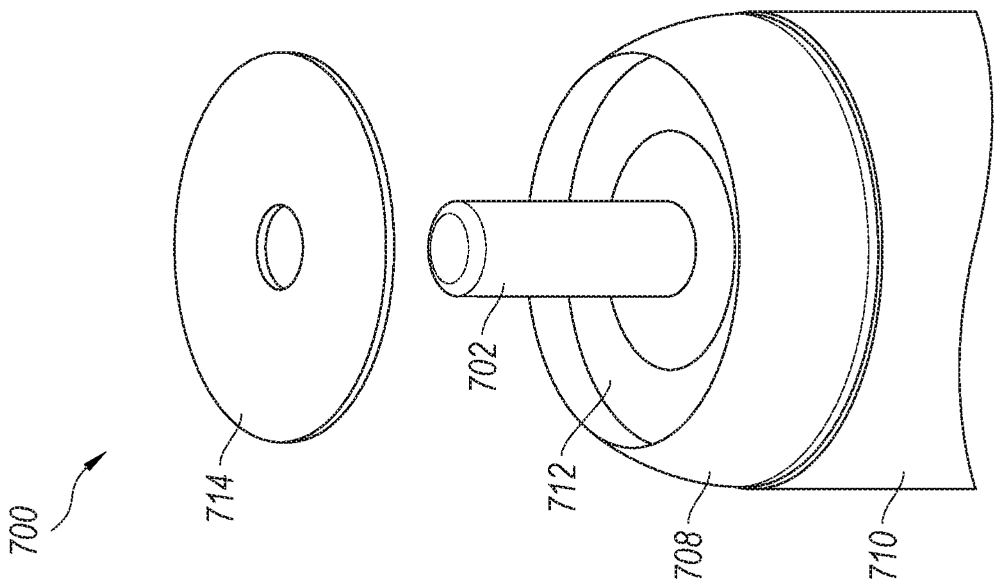

FIGURE 7B

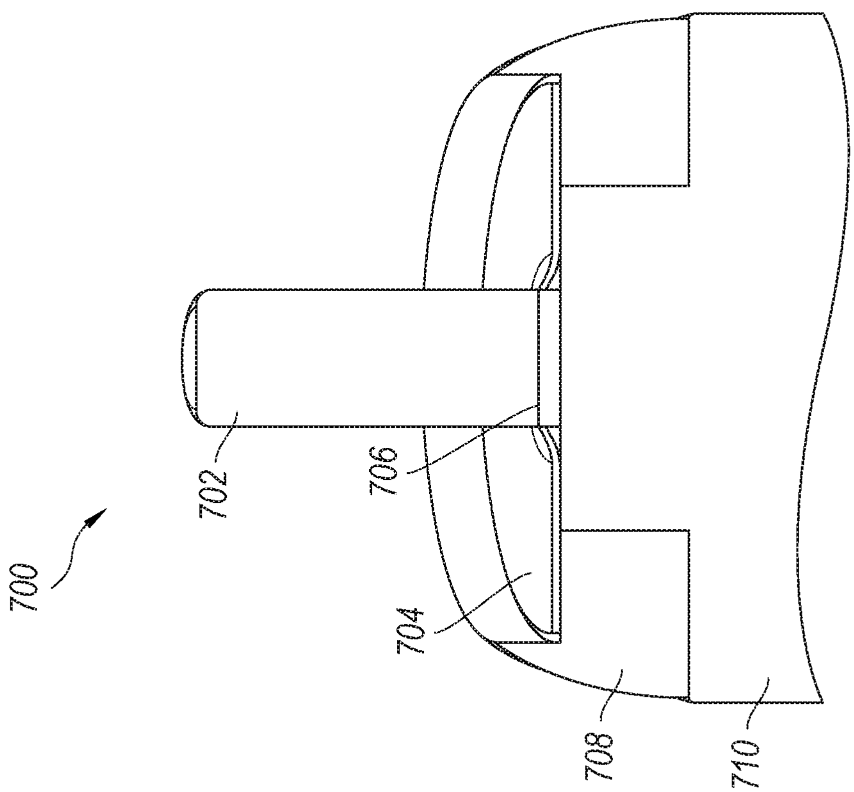

FIGURE 7A

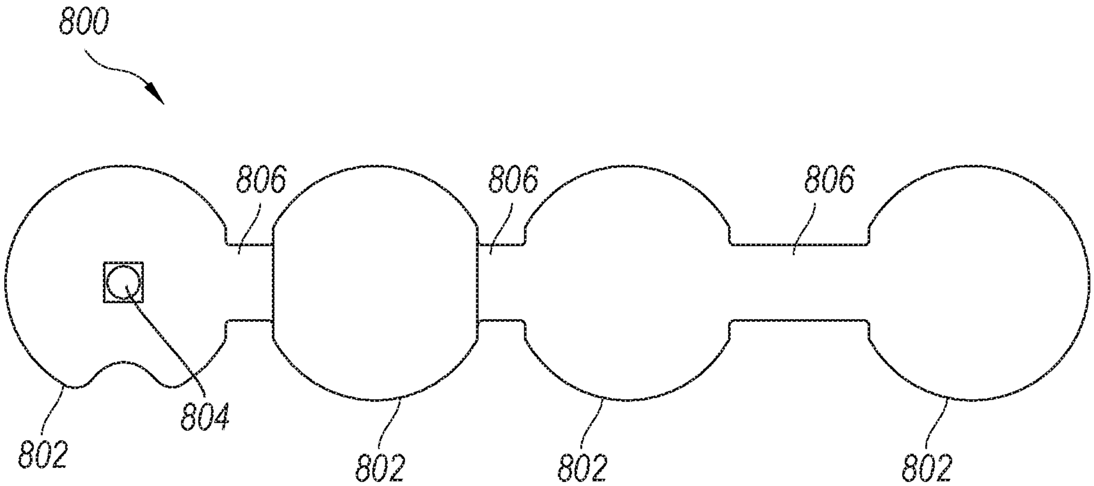

FIGURE 8A

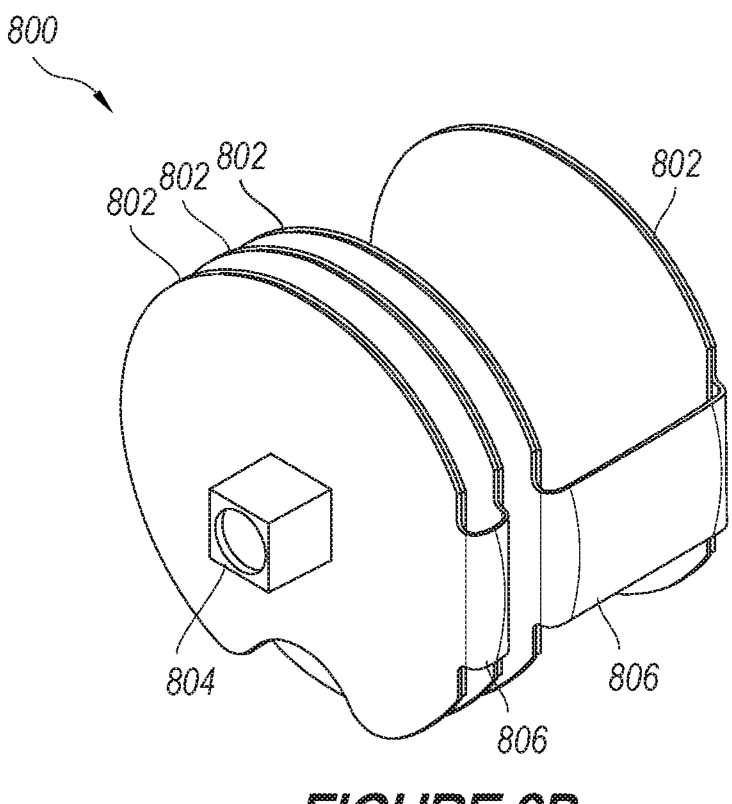

FIGURE 8B

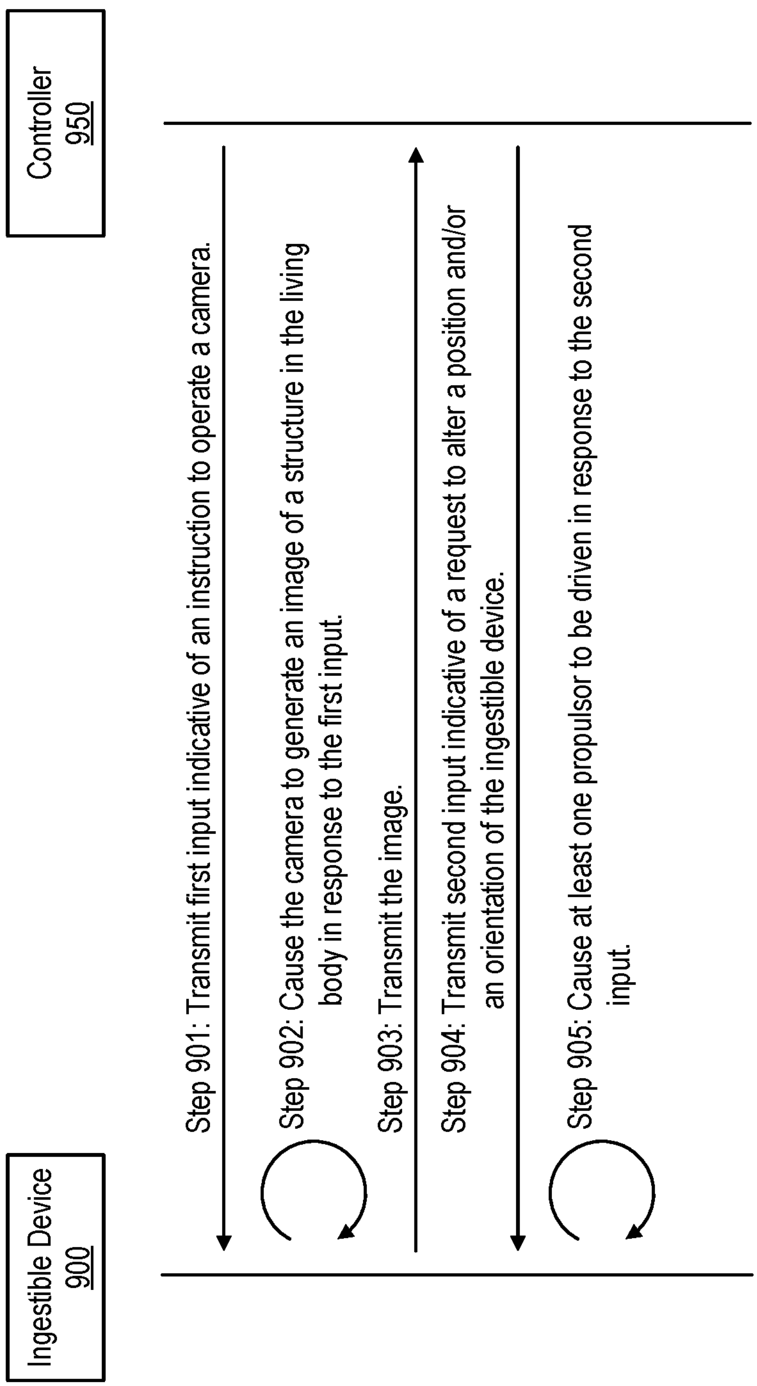
Controller
950
Ingestible Device
900
Step 901: Transmit first input indicative of an instruction to operate a camera.
Step 902: Cause the camera to generate an image of a structure in the living body in response to the first input.
Step 903: Transmit the image.
Step 904: Transmit second input indicative of a request to alter a position and/or an orientation of the ingestible device.
Step 905: Cause at least one propulsor to be driven in response to the second input.

FIGURE 9

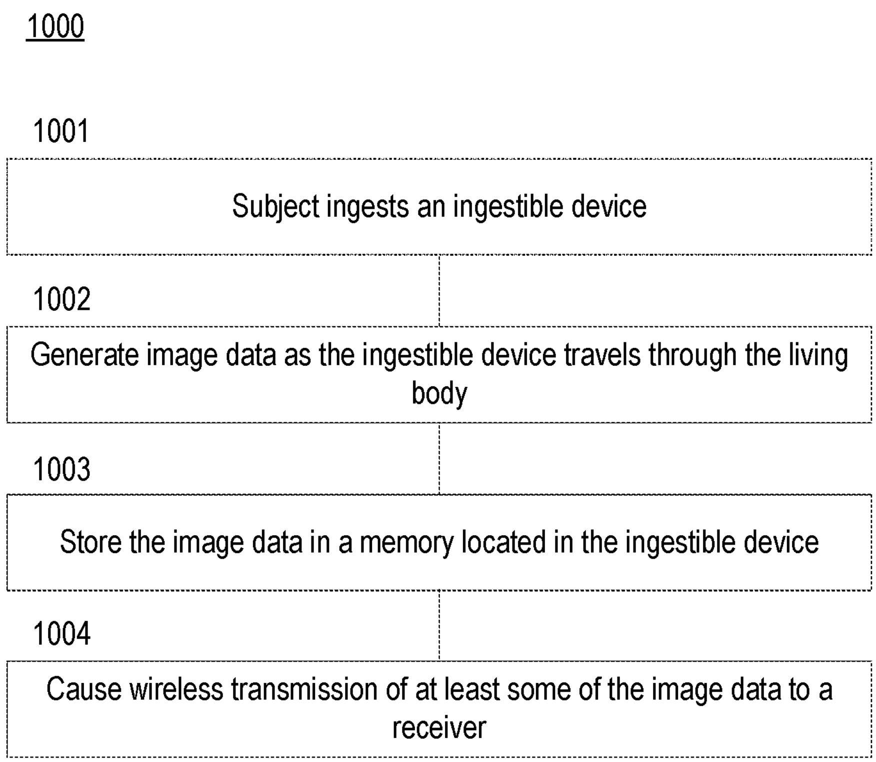
1000
1001
Subject ingests an ingestible device
1002
Generate image data as the ingestible device travels through the living body
1003
Store the image data in a memory located in the ingestible device
1004
Cause wireless transmission of at least some of the image data to a receiver

FIGURE 10

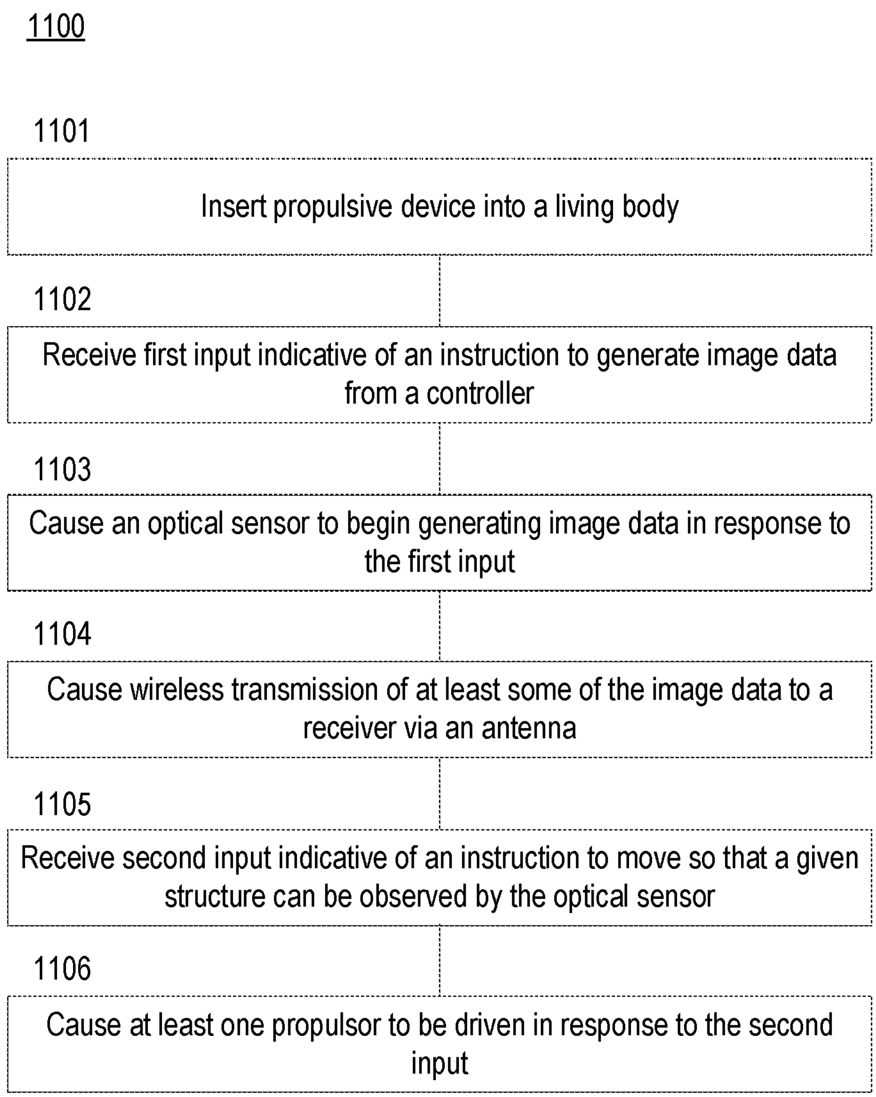
1100
1101
Insert propulsive device into a living body
1102
Receive first input indicative of an instruction to generate image data from a controller
1103
Cause an optical sensor to begin generating image data in response to the first input
1104
Cause wireless transmission of at least some of the image data to a receiver via an antenna
1105
Receive second input indicative of an instruction to move so that a given structure can be observed by the optical sensor
1106
Cause at least one propulsor to be driven in response to the second input

FIGURE 11

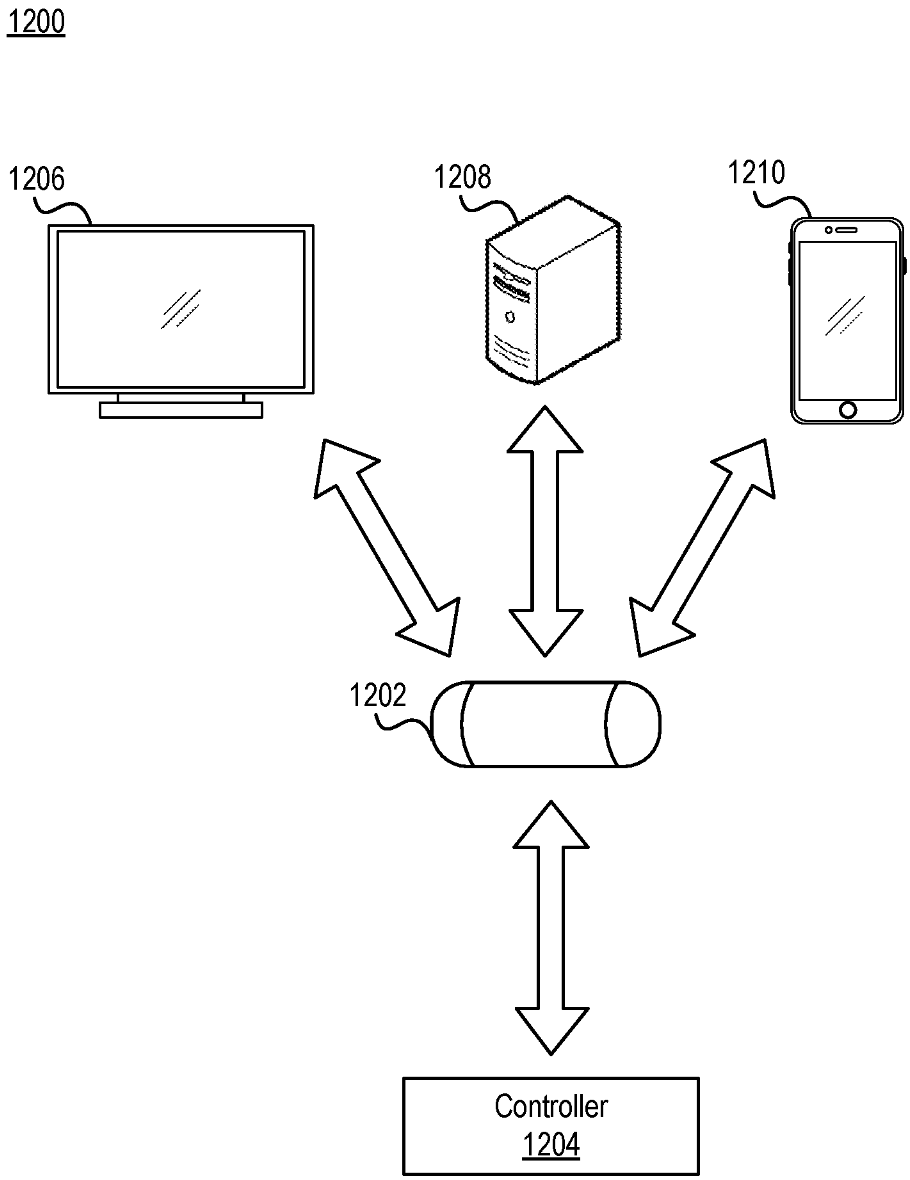

FIGURE 12

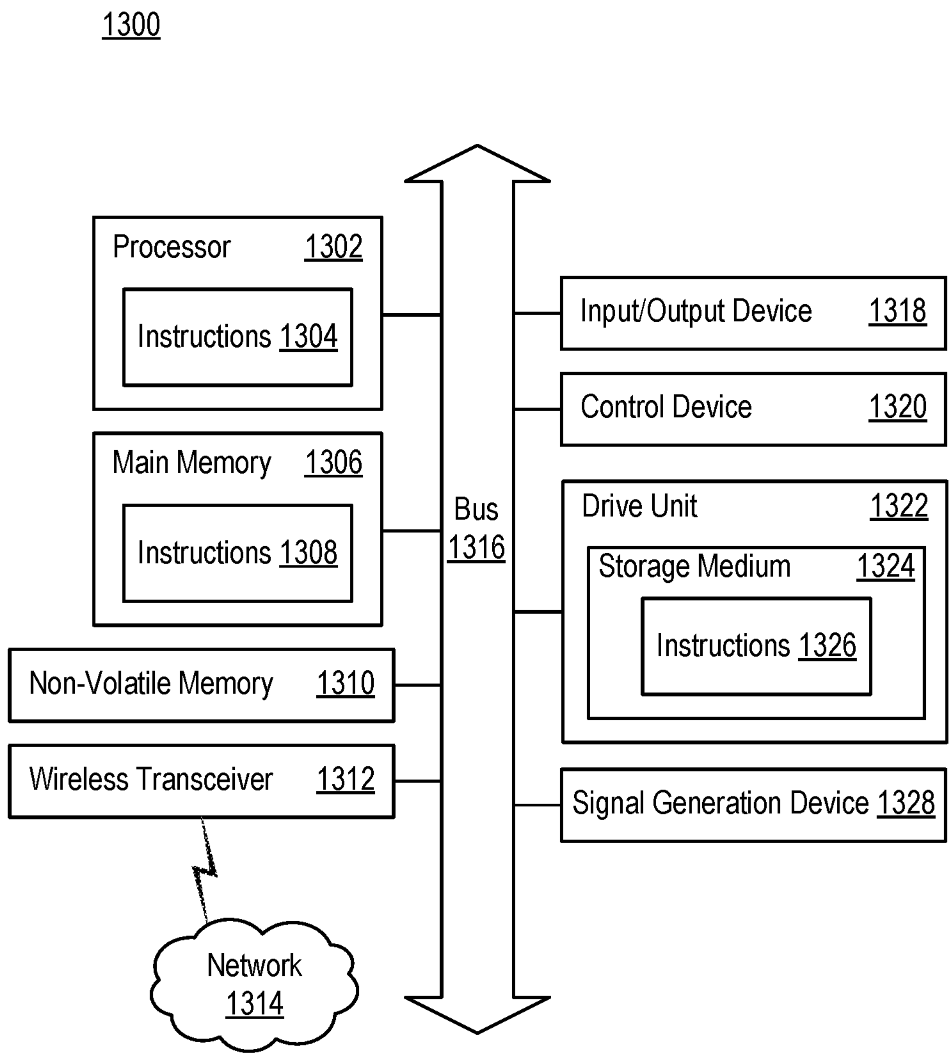
1300
Processor 1302
Instructions 1304
Main Memory 1306
Instructions 1308
Non-Volatile Memory 1310
Wireless Transceiver 1312
Network 1314
Bus 1316
Input/Output Device 1318
Control Device 1320
Drive Unit 1322
Storage Medium 1324
Instructions 1326
Signal Generation Device 1328

FIGURE 13

INGESTIBLE DEVICE WITH PROPULSION CAPABILITIES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 62/868,109, titled "Ingestible Device with Propulsion and Imaging Capabilities" and filed on Jun. 28, 2019, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

Various embodiments concern devices designed to generate images of biological structures located inside of a living body and then transmit the images to an electronic device located outside of the living body.

BACKGROUND

An endoscopy is a medical procedure during which structures within a living body are visually examined with a camera that is affixed to the end of a flexible tube. Alternatively, an optical fiber exposed near the end of the flexible tube may carry light reflected by the structures within the body to a camera located outside the living body. The flexible tube is used to position the camera or the optical fiber in a desired position. A medical professional can diagnose conditions that affect the living body by examining images generated by the camera. For example, during an upper endoscopy, the flexible tube is inserted through the mouth or nose so that the medical professional can examine the esophagus, stomach, or upper part of the small intestine (also referred to as the "duodenum"). During a lower endoscopy (also referred to as a "colonoscopy"), the flexible tube is inserted through the rectum so that the medical professional can examine the large intestine (also referred to as the "colon").

Advances have been made in the quality, reliability, and safety of endoscopies. For instance, improvements in camera resolution have allowed medical professionals to provide more informed (and thus more accurate) opinions. Endoscopies are invasive procedures, however, and therefore have several potential complications. Patients may suffer infection, unexpected reactions to sedation (including death), bleeding (e.g., due to the removal of tissue for testing as part of a biopsy test), or tearing of tissue due to the friction of advancing the flexible tube through tortuosity, especially in cancer patients where chemotherapy drugs have weakened the tissues of the gastrointestinal (GI) tract or in pediatric patients whose anatomy is more fragile and/or physically smaller.

Moreover, endoscopies can be time-consuming procedures that require expensive hospital resources. For example, a patient may be instructed to prepare for an endoscopy while at home, travel to a medical setting, and then remain in the medical setting until sufficient recovery has occurred. This experience can take 8-12 hours despite the endoscopy itself lasting only 15-30 minutes. Recovery time associated with sedation that is spent in a medical setting, such as a hospital or a clinic, may be a significant contributor to the overall cost of the procedure.

BRIEF DESCRIPTION OF THE DRAWINGS

Various features of the technology will become more apparent to those skilled in the art from a study of the

Detailed Description in conjunction with the drawings. Embodiments of the technology are illustrated by way of example and not limitation in the drawings, in which like references may indicate similar elements.

FIG. **1** includes a cross-sectional view of an example of a propulsive ingestible device designed to monitor in vivo environments as it travels through a living body, such as a human body or an animal body, under its own power.

FIG. **2**A includes a front perspective view of a payload section of an ingestible device.

FIG. **2**B includes a rear perspective view of the payload section of the ingestible device of FIG. **2**A.

FIG. **3** includes a perspective view of a power section of an ingestible device.

FIG. **4** includes a perspective view of a drive section of an ingestible device.

FIG. **5**A includes a perspective view of a propulsion section of an ingestible device.

FIG. **5**B includes a transparent perspective view of the propulsion section of the ingestible device of FIG. **5**A.

FIG. **5**C illustrates how propulsors may be arranged adjacent to stator blades in a distal element of an ingestible device.

FIG. **5**D is an isolated rearward view of the distal element of FIG. **5**C.

FIG. **6**A includes a perspective view of an ingestible device having a rounded structural body with a central axis therethrough.

FIG. **6**B includes a side view of the ingestible device of FIG. **6**A.

FIG. **6**C includes a rear view of the ingestible device of FIG. **6**A.

FIG. **7**A includes a cross-sectional view of an ingestible device that illustrates how undersizing a seal formed by a punched or drilled sheet compared to the diameter of the motor shaft enables a single contact line to be created between the seal and motor shaft.

FIG. **7**B illustrates how when the seal is potted inside the main seal body, an orifice disc may be secured within the pocket that is formed.

FIG. **8**A depicts an example of a flexible printed circuit board assembly (PCBA) in an expanded form.

FIG. **8**B depicts the flexible PCBA of FIG. **8**A in a folded form.

FIG. **9** includes a high-level illustration of communications between a device designed for ingestion by a living body and a controller through which movement of the ingestible device is controlled.

FIG. **10** depicts a flow diagram of a process for monitoring an in vivo environment using a device designed for ingestion by a living body.

FIG. **11** depicts a flow diagram of a process for controlling a propulsive ingestible device that has an optical sensor as it travels through a living body.

FIG. **12** depicts an example of a communication environment that includes a propulsive ingestible device that is communicatively coupled to a controller.

FIG. **13** is a block diagram illustrating an example of a processing system in which at least some operations described herein can be implemented.

DETAILED DESCRIPTION

Contemporary research has begun exploring how to monitor in vivo environments in a more effective manner. For example, several entities have developed cameras capable of capturing images of the digestive tract. Generally, these cameras are placed within vitamin-size capsules that can be swallowed by patients. The camera can generate hundreds or thousands of images as the capsule travels through the digestive tract, and these images can be wirelessly transmitted to an electronic device carried by the patient. This procedure is referred to as "capsule endoscopy."

Capsule endoscopy allows medical professionals to observe in vivo environments, such as the small intestine, that cannot easily be reached with conventional endoscopes. However, capsule endoscopy remains a relatively uncommon procedure. One reason for this is the lack of control over the camera following ingestion of the capsule. Areas of interest can be missed by the camera due to the orientation of the capsule as it naturally travels through the digestive tract. Another reason is that the devices used for capsule endoscopy can take several hours to reach the target anatomy and then several more hours to record imagery. Then, the patient may need to return to a medical setting (e.g., a hospital or clinic) to deliver the recorded imagery.

Introduced here, therefore, is a propulsive ingestible device (also referred to as a "pill" or a "pillbot") comprising a capsule (also referred to as an "enclosure"), a camera, an antenna, and one or more propulsion components and propulsion control elements. Because the ingestible device is designed to propel itself through a living body, the ingestible device may be referred to as a "propulsive device."

The camera can generate images as the ingestible device traverses the gastrointestinal tract. The camera may be designed to capture images at a variety of frame rates, for example 2, 6, or 15 frames per second (fps). In some embodiments, the camera may capture more than 15 fps. The frame rate may vary based on the speed at which the ingestible device is traveling. For instance, the ingestible device may be designed to increase the frame rate as the speed increases. Images generated by the camera are forwarded to the antenna for transmission to an electronic device located outside of the living body. More specifically, a processor may transmit the images to a transceiver responsible for modulating the images onto the antenna for transmission to the electronic device. In some embodiments, the images are transmitted to the electronic device in real time so that a medical professional can take appropriate action(s) based on the content of the images. For example, the medical professional may discover an area of interest that requires further examination upon reviewing the images. In such a scenario, the propulsion component(s) can orient the propulsive ingestible device so that the camera is focused on the area of interest. Such action may enable the ingestible device to gather additional data (e.g., in the form of images, biological measurements, etc.) regarding the area of interest.

The medical professional may be a general practitioner, specialist (e.g., a surgeon or a gastroenterologist), nurse, or technologist who is responsible for managing the ingestible device as it travels through the living body. Unlike conventional endoscopies, however, the medical professional need not be located in close proximity to the patient (also referred to as a "subject") undergoing examination. For example, the medical professional may examine images generated by the camera on an electronic device located in a remote hospital while the patient lies in another environment, such as a home, battlefield, etc. In this way, capabilities of a traditional GI department may be extended using the technologies described herein.

Embodiments may be described with reference to particular capsule shapes, propulsion components, sensors, networks, etc. However, those skilled in the art will recognize that the features of these embodiments are equally applicable to other capsule shapes, propulsion components, sensors, networks, etc. For example, although a feature may be described in the context of an ingestible sensor that has multiple propellers arranged in a cross-type configuration, the feature may be embodied in an ingestible sensor having another type of propulsor, or propellers in a different arrangement, or a combination of these variations.

Ingestible Device Overview

FIG. **1** includes a cross-sectional view of an example of an ingestible device **100** designed to monitor in vivo environments as it travels through a living body, such as a human body or an animal body. Note that FIG. **1** and other illustrations in this document are not drawn to scale and are shown significantly enlarged for greater clarity. Because the ingestible device **100** can be designed to propel itself through a living body, the ingestible device **100** may be referred to as a "propulsive device." The ingestible device **100** includes a capsule **102** with a cylindrical body **104** and hydrodynamic, atraumatically shaped ends **106***a-b*. One example of a hydrodynamic, atraumatically shaped end is a rounded shape that does not cause damage upon contacting living tissue, such as the roughly hemispherical ends shown in FIG. **1**. This geometric shape may be referred to as a "spherocylinder." While the ingestible device **100** shown in FIG. **1** has roughly hemispherical ends, other hydrodynamically-shaped ends may be included in other embodiments. For example, at least one end of the capsule **102** may be a dome with a flat portion through which light can be guided toward an optical sensor. As another example, at least one end of the capsule **102** may be a truncated cone. At least one end of the capsule **102** may also feature fillets that leave flat or minimally curved surfaces along those end(s). The cylindrical body **104** and hemispherical ends **106***a-b* may collectively be referred to as the "structural components" of the capsule **102**. To avoid contamination of an internal cavity defined by the cylindrical body **104** and/or hemispherical ends **106***a-b*, the structural components may be hermetically sealed to one another.

In some embodiments, these structural components comprise the same material. For example, the structural components may comprise plastic (e.g., polyethylene (PE), polyvinyl chloride (PVC), polyetheretherketone (PEEK), acrylonitrile butadiene styrene (ABS), polycarbonate, nylon, etc.), stainless steel, titanium-based alloy, or another biocompatible material. The term "biocompatible," as used herein, means not harmful to living tissue. Biocompatible polymers may be three-dimensional (3D) printed, machined, sintered, injection molded, or otherwise formed around components of the ingestible device **100**. In other embodiments, these structural components comprise different materials. For example, the hemispherical end **106***a* in which an optical sensor **110** is mounted may be comprised of a transparent plastic, while the other hemispherical end **106***b* and cylindrical body **104** may be comprised of a polymer or metallic alloy. Moreover, these structural components may include a coating that inhibits exposure of the structural components themselves to the in vivo environment. For example, these structural components may be coated with silicone rubber, diamond-like carbon, Teflon, or some other biocompatible, hydrophobic, or hydrophilic coating that aids in safety, durability, or operational efficiency of the ingestible device **100**. Additionally or alternatively, these structural components may be coated with an antibacterial material, such as antibiotic-loaded polymethyl methacrylate (PMMA).

As shown in FIG. **1**, at least one hemispherical end **106***a* can include an opening **108** through which the field of view of an optical sensor **110** extends. In some embodiments, the opening **108** is filled with a transparent material, such as glass or plastic. Alternatively, the optical sensor **110** may be positioned such that its outermost lens substantially aligns with the exterior surface of the hemispherical end **106***a*, or the optical sensor **110** may be positioned such that the focal length of the lens is similar to the radius of the hemispherical end **106***a* such that focus is ensured for any anatomy that directly contacts the ingestible device **100**. While the hemispherical end **106***a* shown in FIG. **1** includes a single opening, other embodiments of the hemispherical end **106***a* may include multiple openings (e.g., for multiple optical sensors, biometric sensors, or combinations thereof). In some embodiments, the hemispherical end **106***a* is entirely comprised of a transparent material. In such embodiments, the hemispherical end **106***a* may not include a dedicated opening for the optical sensor **110** since the optical sensor **110** can generate image data using electromagnetic radiation that has penetrated the transparent material. The hemispherical end **106***a* may include surface features that diffuse or direct illumination leaving the ingestible device **100**. Moreover, a portion of the hemispherical end **106***a* may be rendered substantially opaque to inhibit or eliminate interval reflections of light that may interfere with the optical sensor **110**.

Due to the convenience in manufacturing, the opening **108** will often be circular. However, the opening **108** could have other forms. For example, in some embodiments the opening **108** is rectangular, while in other embodiments the opening **108** has a rectangular portion with circular endpoints. These circular endpoints may be oriented on opposing sides of the hemispherical end **106***a* so that optical sensors positioned beneath the circular endpoints can observe the in vivo environment along both sides of the propulsive ingestible device **100**.

In various embodiments, the capsule **102** may have any of a variety of different sizes, such as any of those listed in Table I.

TABLE I

Example sizes of capsules.

Size	000	00	0	1	2	3	4
Internal Cavity Capacity (ml)	1.37	0.91	0.68	0.50	0.37	0.30	0.21
Length (mm)	35	30	29	26.5	24	21.5	19.5
Diameter (mm)	15	13.5	11	7	6.5	6	5.5

As shown in FIG. **1**, the ingestible device **100** can include four sections having different responsibilities: a payload section **200**, a power section **300**, a drive section **400**, and a propulsion section **500**. Each of these sections is described in greater detail below with respect to FIGS. **2**, **3**, **4**, and **5**, respectively. While these sections are illustrated as being distinct from one another, the component(s) associated with each section may not necessarily be located within the corresponding box shown in FIG. **1**. For example, the power section **300** may include a power distribution unit that extends into the payload section **200**, drive section **400**, and/or propulsion section **500** to deliver power to component(s) in those sections.

FIG. **2**A includes a front perspective view of the payload section **200** of the ingestible device, while FIG. **2**B includes a rear perspective view of the payload section **200** of the ingestible device. The payload section **200** can include an optical sensor **202**, a power and data bus **204**, a control unit **206**, a manipulator controller **208**, a hermetic seal **210**, and an illumination source **212**. Embodiments of the ingestible device can include some or all of these components, as well as other components not shown here. For example, if the ingestible device has been designed solely for imaging, then the payload section **200** may not include a manipulator controller **208** since no manipulation will be performed.

As the ingestible device traverses the gastrointestinal tract, the optical sensor **202** can generate image data based on electromagnetic radiation reflected by structures located in the gastrointestinal tract. For example, if the optical sensor **202** is a camera, then images or video may be captured as the ingestible device travels through the body. Another example of an optical sensor **202** is an infrared sensor. Other embodiments of the ingestible device may include an acoustic sensor, such as an ultrasonic sonic, instead of, or in addition to the optical sensor **202**. Thus, the ingestible device may include one or more sensors configured to generate image data based on energy reflected by structured in the body. An illumination source **212** (also referred to as a "light source") housed in the ingestible device will typically be responsible for generating the electromagnetic radiation. An example of an illumination source **212** is a light-emitting diode (LED). Here, the illumination source **212** is arranged so that the electromagnetic radiation is emitted through the same aperture in the capsule through which the reflected electromagnetic radiation is received. In other embodiments, the illumination source **212** is arranged so that the electromagnetic radiation is emitted through a first aperture in the capsule while the reflected electromagnetic radiation is received through a second aperture in the capsule.

Some embodiments of the propulsive ingestible device include multiple optical sensors **202**. For example, an ingestible device may include a camera equipped with a charge-coupled device (CCD) or a complementary metal-oxide-semiconductor (CMOS) sensor assembly capable of detecting electromagnetic radiation in the visible range and an infrared sensor capable of detecting electromagnetic radiation in the infrared range. These optical sensors can generate distinct sets of data that collectively provide meaningful information that may be useful in rendering diagnoses, as well as assisting with spatial positioning. Here, for instance, the infrared sensor may be able to measure the heat emitted by objects that are included in the colored images captured by the camera.

The power and data bus **204** (also referred to as a "bus" or "bus connector") may be responsible for distributing data and/or power to various components in the propulsive ingestible device. For example, the bus **204** may forward image data generated by the optical sensor **202** to the control unit **206**, and the control unit **206** may forward the image data to a transceiver configured to modulate the data onto an antenna for transmission to a receiver located outside of the body. As further described below, the receiver may be part of an electronic device on which an individual can view images corresponding to the image data, control the ingestible device, etc. The bus **204** may include cables, connectors, wireless chipsets, processors, etc. In some embodiments, the bus **204** manages data and power on separate channels. For example, the bus **204** may manage data using a first set of cables and power using a second set of cables. In other embodiments, the bus **204** manages data and power on a single channel (e.g., with components capable of simultaneously transferring data and power).

The control unit **206** may be responsible for managing other components in the propulsive ingestible device. For example, the control unit **206** may be responsible for parsing inputs received by the antenna and then providing appropriate instructions to other components in the propulsive ingestible device. As further described below, an individual may provide the input using a controller device (or simply "controller") located outside of the body. The input may be representative of a request to begin generating image data using the optical sensor **202**, begin transmitting image data using the antenna, cease generating image data using the optical sensor **202**, cease transmitting image data using the antenna, or move the propulsive ingestible device to a desired location. The control unit **206** may include a central processing unit (CPU), graphics processing unit (GPU), application-specific integrated circuit (ASIC), field-programmable gate array (FPGA), microcontroller, logic assembly, or any combination of other similar processing units.

In some embodiments, the propulsive ingestible device is designed to manipulate in vivo environments in some manner. In such embodiments, the payload section **200** could include an intervention component such as a biopsy appendage, needle, cutting mechanism, pushing mechanism, cauterization mechanism (e.g., an ohmic cauterizer or radio-frequency cauterizer), drug delivery mechanism, etc. The manipulator controller **208** can control these intervention components. For example, the manipulator controller **208** may control a biopsy appendage that extends through the capsule to collect tissue based on instructions received from the control unit **206**.

To prevent fluids from entering the capsule, the payload section **200** and power section **300** may be hermetically sealed to one another. Accordingly, a hermetic seal **210** may be secured along the interface between the payload section **200** and power section **300**. The hermetic seal **210** may be comprised of epoxy resin, metal, glass, plastic(s), rubber(s), ceramic(s), glue or another sealing material. One factor in determining whether the material(s) used to form the hermetic seal **210** are appropriate is whether the surface energy of those material(s) is similar to the surface energy of the substrate to which the hermetic seal **210** is bound. Accordingly, the composition of the hermetic seal **210** may depend on the composition of the structural components of the capsule. For example, if the structural components of the capsule comprise stainless steel, then the hermetic seal **210** may be comprised of an epoxy resin having metal (e.g., stainless steel) particles suspended therein. Alternatively, the hermetic seal **210** may be formed using a flexible gasket, adhesive film, weld, seal, etc.

FIG. **3** includes a perspective view of the power section **300** of the ingestible device. The power section **300** can include a power component **302**, a power distribution unit **304**, and a hermetic seal **306***a-b* secured along each end. The hermetic seals **306***a-b* may be substantially similar to the hermetic seal **210** secured to the payload section **200** as described with respect to FIG. **2**. Moreover, the hermetic seal **210** secured to the lower end of the payload section **200** may be the same seal as the hermetic seal **306***a* secured to the upper end of the power section **300**. Thus, a single hermetic seal may join the payload section **200** and power section **300**.

The power component **302** (also referred to as an "energy storage component") can be configured to supply power to other components of the propulsive ingestible device, such as any optical sensor(s), biometric sensor(s), processor(s), communication components (e.g., transmitters, receivers, transceivers, and antennas), and any other components requiring power. For example, the power component **302** may be responsible for providing power needed by an optical sensor (e.g., optical sensor **202** of FIG. **2**) to generate image data. As another example, the power component **302** may be responsible for generating the driving energy to be applied to an antenna to cause wireless transmission of the image data to a receiver located outside of the body.

The power component **302** could be, for example, a silver-oxide battery, nickel-cadmium battery, lithium battery (e.g., with liquid cathode cells, solid cathode cells, or solid electrolyte cells), capacitor, fuel cell, piezoelectric component, or another energy-capture and/or -storage device. In some embodiments, the power component **302** includes one or more battery plates that are exposed to the fluid(s) through which the ingestible device travels. In such embodiments, the power component **302** can be designed to run on a fluid (e.g., a bodily fluid such as stomach acid) that is readily accessible within the in vivo environment for which the ingestible device is designed. Normally, a battery operates by shuttling ions with a positive charge from one place to another through a solution called an electrolyte that has positively- and negatively-charged particles. In the case of exposed battery plates, however, a pair of metal electrodes can be secured to the exterior surface of the ingestible device. One metal electrode (e.g., comprised of zinc) can emit ions into the fluid, which acts as the electrolyte by carrying a small electric current to the other metal electrode (e.g., comprised of copper).

In some embodiments, the power component **302** is designed such that it can wirelessly receive power from a source located outside of the body. In such embodiments, the source can generate a time-varying electromagnetic field that transmits power to the power component **302**. The power component **302** can extract power from the electromagnetic field and then supply the power to the other components in the ingestible device as necessary. The power may be received using either the same antenna as is used for data transmission or using a different antenna, inductively coupled coil, or capacitively coupled structure. The source could be the controller used for controlling the ingestible device, the electronic device used for reviewing image data, or some other electronic device (e.g., a mobile phone or a wireless charger belonging to the patient). Alternatively, the wireless power source may be included in an article, such as a belt or band, that can be worn such that the wireless power source is located near the ingestible device as it travels through the living body. Such a wearable article may include a battery pack that is integrated within the article itself or attached to the patient. Moreover, such a wearable article may include one or more antennas for data transmission.

The power component **302** may be designed to fit in a particular segment of the ingestible device. Here, for example, the power component **302** has a button cell form that permits the power component **302** to be secured within the cylindrical body of the capsule. However, other embodiments of the power component **302** may be designed to fit within a hemispherical end of the capsule or another area within the capsule.

As noted above, the power distribution unit **304** may be responsible for distributing power stored in the power component **302** to other components in the ingestible device. Accordingly, component(s) of the power distribution unit **304** may extend into the payload section **200**, drive section **400**, and/or propulsion section **500**. For example, the power distribution unit **304** may include cables that are connected to the optical sensor, bus connector, control unit, control sensors, and/or manipulator controller that may be located in the payload section **200**. The power distribution unit **304** may also include component(s) for regulating, stabilizing, or modifying the power to be distributed. Examples of such components include voltage regulators, converters (e.g., DC-to-DC converters), metal-oxide-semiconductor field-effect transistors (MOSFETs), capacitors, transformers, resistors, or inductors.

FIG. **4** includes a perspective view of the drive section **400** of the ingestible device. The drive section **400** can include energy-to-movement converter(s) **402**, heat transfer component(s) **404**, and a hermetic seal **406***a-b* secured along each end. The hermetic seals **406***a-b* may be the same as or substantially similar to the hermetic seal **210** secured to the payload section **200** as described with respect to FIG. **2**. Moreover, the hermetic seal **306***b* secured to the lower end of the power section **300** may be the same seal as the hermetic seal **406***a* secured to the upper end of the drive section **400**. Thus, a single hermetic seal may join the power section **300** and drive section **400**.

Upon receiving power from a power distribution unit (e.g., the power distribution unit **304** of FIG. **3**), the mechanical power converter(s) **402** can drive another component of the ingestible device. Here, for instance, the drive section **400** includes multiple motors, and each motor may be responsible for driving a different propulsor. Examples of motor(s) **402** include DC or AC electric motors, drivers comprised of a shape-memory alloy, electromagnets, shafts, piezoelectric components, etc. The propulsor may be connected to the motor by one or more shafts, gears, levers, bearings, etc.

Components in the ingestible device may produce heat that should be dissipated to avoid causing damage within the body. For example, components such as energy-to-movement converters and motor housings may generate heat if the propulsor(s) are driven for an extended period of time. Accordingly, these components may include or be connected to heat transfer component(s) **404** that are able to assist in dissipating this heat. In some embodiments, the heat transfer component(s) **404** discharge the heat directly into the fluid (e.g., water, bile, stomach acid, and mixtures thereof) surrounding the ingestible device. For example, the motor housings may be comprised of a material (e.g., stainless steel) having acceptable thermal conductivity to promote dissipation of heat. In other embodiments, the heat transfer component(s) **404** discharge the heat into the capsule. When heat is discharged into the capsule, the heat may naturally transfer into the fluid surrounding the ingestible device through conduction and convection.

FIG. **5**A includes a perspective view of the propulsion section **500** of the ingestible device, while FIG. **5**B includes a transparent perspective view of the propulsion section **500** of the ingestible device. The propulsion section **500** can include one or more propulsors **502**, one or more intakes **504**, and a hermetic seal **508** secured along its upper end. The hermetic seal **508** may be substantially similar to the hermetic seal **210** secured to the payload section **200** as described with respect to FIG. **2**. Moreover, the hermetic seal **508** may be the same seal as the hermetic seal **406***b* secured to the lower end of the drive section **400**. Thus, a single hermetic seal may join the drive section **400** and propulsion section **500**.

As noted above, the ingestible device may include one or more propulsion components (also referred to as "propulsion systems" or "thrust components"). Each propulsion component can include a propulsor configured to generate a propulsive force for moving the ingestible device and an energy-to-movement converter configured to supply motive power to the propulsor. Here, for example, the propulsion section **500** includes four rotors **502** that are driven by four motors located in the drive section **400**. In some embodiments, each propulsor is driven by a different mechanical power converter. In other embodiments, multiple propulsors may be driven by a single energy-to-movement converter. For example, a single motor may be responsible for supplying motive power to multiple propulsors, though the speed of each propulsor may be varied through a mechanical connection (e.g., a clutch system or a gear system).

As further described below, multiple propulsors **502** can be arranged to facilitate movement along different axes. In FIGS. **5**A-B, for example, four propulsors **502** are arranged radially about a central axis **516** defined through the capsule in a cross-type configuration. More specifically, these propulsors **502** are disposed at locations radially offset from the central axis and at different angular offsets about the central axis. By independently driving these propulsors **502**, movement can be achieved in any direction or orientation, in a fashion similar to a quadcopter. Accordingly, the ingestible device may be commanded to move forward and backward at different speeds. Moreover, the ingestible device may be commanded to change its orientation through rotation about three mutually perpendicular axes. These changes in orientation and forward/backward motions can be converted into variations in yaw (normal axis), pitch (transverse axis), and roll (longitudinal axis), and therefore movement to any location can be represented in three-dimensional space.

In FIGS. **5**A-B, the propulsors **502** are rotors capable of drawing fluid through intakes **504** formed in the capsule. The term "rotor," as used herein, refers to a component that is capable of rotating to create propulsive force. An example of a rotor is a propeller. However, other propulsors could be used instead of, or in addition to, the rotors. Examples of propulsion components include helicoids, fins, lash-like appendages (also referred to as "flagellum"), undulating mechanisms, etc. Moreover, propulsion components could be arranged along the cylindrical body of the capsule instead of, or in addition to, in the hemispherical end of the capsule. For example, an ingestible device may include oscillating fins arranged along opposing sides of the cylindrical body of the capsule. These oscillating fins may be used in conjunction with propeller(s), helicoid(s), or lash-like appendage(s) located in the hemispherical end of the capsule to provide greater control over the movement of the ingestible device.

As shown in FIGS. **5**A-B, the capsule may include one or more channels through which fluid can be drawn by the propulsion(s) **502**. Each channel includes an inlet **504** through which fluid can be drawn and an outlet **506** through which the fluid is discharged. Examples of inlets **504** include ducts, lumens, vanes, tubes, etc. While the embodiment shown in FIG. **5** includes an identical number of propulsors **502** and inlets **504**, that need not always be the case. For example, a propeller mounted in the hemispherical end of the capsule may be able to draw fluid through one or more inlets to prevent moving components, such as the propulsor(s) **502**, from touching living tissue. Rotational propeller efficiency may be optimized with fixed stator vanes so as to control swirl, increase velocity, and increase controllability, as further discussed below with respect to FIGS. **5**C-D. In some embodiments, coaxial contra-rotating propellers may be used to obviate fixed stator vanes altogether. Propeller and vane blade count and geometry may be tuned to optimize clearing of bubbles and debris as a function of diameter, speed, and fluid properties.

In some embodiments, a filter is placed in at least one of the channels defined through the capsule. For example, a filter may be secured in each channel defined through the capsule. Filters may be necessary to ensure that objects suspended in the fluid drawn through the inlets **504** that exceed a particular size are removed. For example, if the ingestible device is designed for use within the gastrointestinal tract, the filter(s) may be designed to prevent solid particulates such as food particles from contacting the propulsor(s) **502**.

Another issue is that propulsors tend to impart rotational motion on (or "stir") the fluid rather than create thrust unless designed properly. This problem can be addressed by adding one or more stator vanes (also referred to as "stator blades") to each flow channel. The terms "stator vane" and "stator blade" refer to a fixed blade positioned within the flow channel through which fluid is drawn and then ejected by a propeller. FIG. **5**C illustrates how propulsor(s) **502** may be arranged adjacent to stator vanes **514** in a distal element **512** of the ingestible device of FIGS. **5**A-B. These stator vanes **514** may serve to straighten the fluid flow, reduce the stirring effect, and increase thrust and thrust consistency. As shown in FIG. **5**C, each propulsor **402** may be connected to a separate motor housing **510** in which the motor responsible for driving the propulsor is located. The propulsors **502** (and thus the motor housings **510**) may be arranged in a cross-type configuration to better control the propulsive force.

FIG. **5**D is an isolated, rearward view of the distal element **512** shown in FIG. **5**C. In embodiments where the distal element **512** includes multiple stator vanes **514**, the stator vanes **514** may be radially arranged around a geometric center of the distal element **512**. Generally, the stator vanes **514** are arranged roughly evenly about the geometric center as shown in FIG. **5**D. However, in some embodiments, the stator vanes **514** are arranged about the geometric center in an uneven manner.

FIGS. **6**A-C include perspective, side, and rear views of an ingestible device **600** having an atraumatic structural body **602** with a central axis **612** therethrough. The structural body **602** shown in FIGS. **6**A-C is a spherocylinder that includes a cylindrical segment interconnected between hemispherical segments. In other embodiments, the structural body **602** may be in the shape of an oval, rectangle, teardrop, etc.

As noted above, the ingestible device **600** can include one or more propulsors for controlling movement along three mutually perpendicular axes. Here, for example, the ingestible device **600** includes four rotors **604***a-d* arranged radially about the structural body **602** orthogonal to the central axis **612**. The four rotors **604***a-d* may include a first pair of rotors **604** *a-b* arranged radially opposite each other relative to the central axis **612** and a second pair of rotors **604** *c-d* arranged radially opposite each other relative to the central axis. Each pair of rotors may be configured to share identical chirality; for example, rotors **604***a-b* may both generate forward thrust when rotating clockwise relative to the central axis **612**. Simultaneously, the rotor pairs may be configured to have opposite chirality; for example, rotors **604***a-b* may generate forward thrust while rotors **604***c-d* may generate backward thrust when all four rotors are rotating clockwise relative to the central axis **612**. As shown in FIG. **6**C, the first and second pairs of rotors **604***a-d* may be arranged in a cross-type configuration so that neighboring rotors rotate in opposite directions to produce thrust in the same direction, while radially opposite rotors rotate in the same direction to produce thrust in the same direction. Such a configuration allows independent control of thrust, pitch, yaw, and roll through the combination of the effects of the individual rotors; thus, control of position and orientation may be achieved in a fashion similar to a quadcopter.

Each rotor may be located in a different channel defined through the structural body **602**, and each channel may include an inlet **606** through which fluid is drawn by the corresponding rotor and an outlet **608** through which the fluid is discharged by the corresponding rotor. Generally, the channels are defined through the structural body **602** in a direction substantially parallel to the central axis. Here, for example, the inlet **606** of each channel is located in a cylindrical segment of the structural body **602** while the outlet **608** of each channel is located in a hemispherical segment of the structural body **602**. When in operation, the rotors **604***a-d* can draw fluid through the inlets **606** to create flows **610** that propel the ingestible device in a particular direction. In some embodiments, the channels are tapered. For example, the inlet **606** of each channel may have a smaller diameter than the outlet **608**, or the inlet **606** of each channel may have a larger diameter than the outlet **608**.

In some embodiments, each rotor is designed to rotate in a primary direction and a secondary direction. For example, the first pair of rotors **604***a-b* may be configured to be able to rotate in the clockwise and counterclockwise directions in relation to the central axis **612**. Similarly, the second pair of rotors **604***c-d* may be able to rotate in the counterclockwise and clockwise directions in relation to the central axis **612**. Accordingly, while the flows **610** are shown as flowing toward a first end **614** (also referred to as the "distal end") of the ingestible device **600**, the flows **610** could instead be flowing toward a second end **616** (also referred to as the "proximal end") of the ingestible device **600**.

As noted above, the term "rotor," as used herein, refers to a component that is capable of rotating to create propulsive force. The propulsive force imparts momentum to the surrounding fluid(s) to produce movement. The structural body **602** can be fitted with one, two, three, four, or more rotors depending on the speed and maneuvering requirements of the ingestible device **600**. In FIGS. **6**A-C, for example, four rotors are arranged in a cross-type configuration within the first end **614** of the structural body **602**. In other embodiments, three rotors are arranged in a triangular configuration within the first end **614** of the structural body **602**.

Each rotor may be independently driven by a different motor. In FIGS. **6**A-C, for example, the ingestible device **600** includes four motors configured to supply motive power to the four rotors **604***a-d*. In other embodiments, multiple rotors may be driven by a single mechanical power converter. For example, a single motor may be responsible for supplying motive power to the first pair of rotors **604***a-b*, though the speed of these rotors may be varied through a mechanical connection (e.g., a clutch system or a gear system).

In some embodiments, each rotor has a fixed pitch. In FIGS. **6**A-C, for example, the four rotors **604***a-d* are fixedly arranged along a radial plane orthogonal to the central axis **612**. In other embodiments, at least one rotor has a variable pitch. In such embodiments, greater control over movement of the ingestible device **600** can be achieved by simultaneously controlling the pitch and rotation of the rotors **604***a-d*.

The rotors may consist of one or more biocompatible materials. Examples of biocompatible materials include titanium alloys, stainless steel, ceramics, polymers, fiber-reinforced polymers (e.g., fiberglass or carbon fiber) plastics (e.g., polycarbonate, nylon, PEEK, or ABS), resins, composites, etc. Moreover, each rotor may have an antibacterial, hydrophobic, or hydrophilic coating applied thereto. For example, each rotor may be coated with antibiotic-loaded

PMMA. The coating(s) applied to the rotors may depend on the type of in vivo environment for which the ingestible device **600** is designed.

Generally, to produce a rotor, a number of blades are secured to the hub through welding, gluing, or, alternatively, by forging the entire rotor in one piece. The number of blades may depend on the desired efficiency, speed, acceleration, maneuverability, etc. For example, 3-blade rotors exhibit good acceleration in comparison to other types of rotors, while 4-blade rotors exhibit good maneuverability in comparison to other types of rotors. Rotors with a higher blade count (e.g., those with 5 or 6 rotor blades) exhibit good holding power in turbulent in vivo environments, such as those with high flow rates. A single-blade rotor may have advantages in manufacturability and durability. In the embodiment shown in FIGS. **6**A-C, each rotor includes three helicoidal surfaces acting together to rotate through a fluid (e.g., water, bile, etc.) with a screw effect.

One of the difficulties of producing thrust at small scales is the persistent bubbles that can get trapped near rotors such as propellers, preventing the rotors from properly engaging with the fluid. This problem can be addressed by carefully designing the shape, number, and arrangement of blades along each rotor to assist in the clearing of bubbles. Carefully matching the pitch of the blade, shape of lumens, motor speed, clearance between rotor and wall, clearance between rotor and stator vane, and surface material properties affects the generation and clearing of bubbles.

Rotors may be formed based on simple truncated Archimedes screw geometry. Alternatively, as discussed above, rotors may feature a plurality of individual blades featuring curvature optimized to thrust in the forward or rearward direction. Likewise, if stator blades are positioned in the channels through which the rotors draw and then eject fluid, those stator blades may feature flat or curved blades.

Preventing fluid from entering the ingestible device, especially in the propulsion section that includes the moving motor interface, is also critical. Accordingly, the ingestible device may implement tight tolerances, hydrophobic and/or hydrophilic materials, or mechanical seals. Seals can maintain tolerances at the micro scale, and therefore are useful for maintaining safety and consistency without requiring complex assembly processes. FIGS. **7**A-B illustrate how low-profile and low-friction seals can be implemented to prevent fluid from entering the motor housing(s) of an ingestible device **700**.

FIG. **7**A includes a cross-sectional view of the ingestible device **700** that illustrates how undersizing a seal **704** formed by a punched or drilled sheet compared to the diameter of the motor shaft **702** enables a single contact line **706** to be created between the seal **704** and motor shaft **702**. Sealing action, static friction, and dynamic friction can be optimized by tuning the dimensional interference and resulting embedded tension. The punched or drilled sheet may be comprised of polytetrafluoroethylene (PTFE) or a similar material (e.g., ultra-high-molecular-weight (UHMW) polyethylene). This design can be readily produced with relatively few machining operations. Another advantage of this approach is that several seals can be produced at once with a simple drilling jig. By under-drilling a small hole (e.g., 0.5-0.6 mm in diameter for a motor shaft that is 0.7 mm in diameter) in the sheet and then dilating it over the motor shaft **702**, hoop tension (also referred to as "hoop stress") is produced. The hoop tension will cause the dilated hole to protrude slightly, producing a minimal line of contact **706** with the motor shaft **702** and reducing friction while providing a seal.

The seal **704** can be produced using a hypodermic tubing punch. Multiple seals can be drilled simultaneously on a lathe while still in the hypodermic tube using a simple fixture and drill guide. The assembly process may be completed by placing the seal **704** on the motor shaft **702** and then fixing it in place with a curable adhesive (e.g., a UV-curable adhesive), radio-frequency (RF) welding, heat welding, etc. The seal **704** can be dilated over the motor shaft **702** and then potted inside a main seal body **708** with a curable adhesive or another sealing technology.

As shown in FIGS. **7**A-B, the main seal body **708** may be connected to the motor housing **710** with a curable adhesive or another sealing technology. One or more seals may be implemented on a single motor shaft in order to optimize shaft friction and seal reliability. Successive lip seals with different clearances may assist in optimizing energy efficiency, aging, and overall safety and performance. As shown in FIG. **7**B, when the seal **704** is potted inside the main seal body **708**, a pocket **712** may be formed. An orifice disc **714** having a hole defined therethrough for receiving the motor shaft **702** may be positioned within the pocket to further inhibit leaking into the motor housing **710**. The orifice disc **714** may be comprised of plastic, metal, rubber, Viton, Teflon, UHMW polyethylene, high-density polyethylene, or similar materials.

Accordingly, a manufacturer may obtain a flexible substrate having a substantially circular shape, form a hole at a geometric center of the flexible substrate (e.g., by punching or drilling the hole), and then dilate the hole in the flexible substrate around a motor shaft having a larger diameter than the hole. Such an approach may cause an elastic interference fit to be created between the flexible substrate and motor shaft, thereby forming a seal. Then, the manufacturer may secure the flexible substrate along an outer perimeter to form a hermetic seal. For example, as noted above, the flexible substrate could be secured with a curable adhesive, RF welding, heat welding, etc.

Some or all of the electronic components described herein as being contained within an ingestible device may be mounted on flexible printed circuit board assemblies (PCBAs). FIGS. **8**A-B depict an example of a flexible PCBA **800** in its expanded and folded forms, respectively. As shown in FIG. **8**A, the flexible PCBA can include at least two rigid areas **802** that serve to provide support to components **804** mounted thereon and accompanying solder joints, as well as to help define the structure of the PCBA **800** as a whole. These rigid areas **802** may be connected by flexible areas **806** that can be folded to allow the PCBA **800** to fit within the ingestible device. The PCBA **800** may include conductive connections between the electronic components to allow for the transfer of power and/or data therebetween. More specifically, the PCBA **800** may include one or more conductive layers that serve as connections between the electronic components mounted to the rigid areas **802**. Each pair of conductive layers may be separated by an insulating layer (also referred to as a "non-conductive layer") comprised of a non-conductive material such as polyimide.

FIG. **9** includes a high-level illustration of communications between a device **900** designed for ingestion by a living body and a controller **950** through which movement of the ingestible device **900** is controlled. Because images generated by the ingestible device **900** may be reviewed on the controller **950**, the controller **950** could also be referred to as a "data review station" or "data review unit." Initially, the controller **950** transmits first input indicative of an instruction to operate a camera housed within the ingestible device

900 (step **901**). Alternatively, the ingestible device **900** may be designed to automatically operate the camera when the device is first powered on or activated by removal from the packaging.

The ingestible device **900** can cause the camera to generate an image of a structure in the living body in response to the first input (step **902**). The structure may be a biological structure or a non-biological structure (also referred to as a "foreign object"). The ingestible device **900** can then transmit the image to the controller **950** for review (step **903**). More specifically, a processor responsible for processing images generated by the camera may forward the image to a transmitter for modulation onto an antenna for wireless transmission to the controller. In some embodiments, the transmitter is part of a transceiver capable of transmitting communications to, and receiving communications from, the controller **950**.

The controller **950** may further transmit second input indicative of a request to alter a position and/or an orientation of the ingestible device **900** (step **904**). This second input may be referred to as a "steering instruction" or a "propulsion instruction." The ingestible device **900** can cause at least one propulsor to be driven in response to the second input (step **905**). In instances where multiple propulsors are driven in response to the second input, the ingestible device **900** may generate multiple signals for driving the multiple propulsors. These signals may be different than each other. For example, each propulsor of the multiple propulsors could be rotated at different speeds. As another example, some propulsors of the ingestible device **900** may be rotated while other propulsors of the ingestible device **900** are held stationary.

FIG. **10** depicts a flow diagram of a process **1000** for monitoring an in vivo environment using a device designed for ingestion by a living body. Initially, a subject ingests the ingestible device as part of a capsule endoscopy procedure for observing the gastrointestinal tract (step **1001**). The ingestible device (and its controlling software) may support several different data collection modes. For instance, the ingestible device may support a "general mode" suitable for open navigation and/or a "swallow mode" suitable for one-way trips through the esophagus.

An optical sensor included in the ingestible device can then begin generating image data as the ingestible device travels through the living body (step **1002**). In some embodiments, the ingestible device causes the optical sensor to begin generating image data in response to receiving an instruction to do so. The instruction may be submitted, for example, by an operator through a controller that is communicatively coupled to the ingestible device. In other embodiments, the ingestible device causes the optical sensor to automatically generate image data in response to determining that a predetermined criterion has been met. For example, the ingestible device may cause the optical sensor to begin generating image data in response to determining that the ingestible device has entered a particular in vivo environment. The ingestible device may reach such a determination by examining biometric data generated by a biometric sensor. For instance, the ingestible device could establish whether it is presently within the stomach by examining biometric data representative of pH measurements. The images may be captured with any of various resolutions, such as 48×48 pixels, 320×240 pixels, or 640×480 pixels. In other embodiments, images may be captured with higher or lower resolutions. The image data may be stored, at least temporarily, in memory located in the ingestible device (step **1003**).

The ingestible device can then cause wireless transmission of at least some of the image data to a receiver located outside of the living body via an antenna (step **1004**). In some embodiments, the receiver is housed within an electronic device associated with the subject. For example, the image data may be transmitted to a mobile phone associated with the subject, and the mobile phone may forward the image data to another electronic device for review by the operator responsible for controlling the ingestible device. In some embodiments, image data is transmitted to the receiver on a periodic basis (e.g., every 3 seconds, 5 seconds, 30 seconds, 60 seconds, etc.). In other embodiments, image data is transmitted to the receiver in real time. That is, the ingestible device may stream image data to the receiver as the image data is being generated by the optical sensor.

To reduce the amount of raw data that must be transferred across the bus or wireless link, the image data (and well as identifying data, telemetry data, etc.) may be compressed in such a way as to reduce the quantity without significantly affecting user perception of quality. For example, algorithms may be employed that reduce color/hue differently than intensity, or reduce high-frequency content differently than low-frequency content. Standardized image and/or video compression algorithms such as JPEG, H.264 (MPEG), H.265, and the like may be employed to compress the data. To further reduce the amount of data, the image resolution may be reduced before it is compressed and transmitted. For example, the optical sensor may generate an image with 640×480 pixel resolution, but the image may be down-sampled to 320×240 pixel resolution prior to JPEG compression. The resolution may be adjusted during operation to achieve a desired tradeoff between image quality and frame rate (e.g., image quality may be reduced in order to increase frame rate while the ingestible device travels through the esophagus). Other compression algorithms may be used after the data has been transmitted over the wireless link, such as in the case where the data is transmitted to a controller that has computing and memory resources available for executing more demanding compression algorithms than is feasible to perform on the ingestible device itself. This additional compression may be used to reduce the size of data that is stored on the controller or some other electronic device. Data may be encrypted, on the ingestible device, the controller, or some other electronic device, to prevent unauthorized third-party access of patient identifying information (PII) or medically sensitive information.

FIG. **11** depicts a flow diagram of a process **1100** for controlling an ingestible device that has an optical sensor as it travels through a living body. Initially, the ingestible device is inserted into the living body (step **1101**). For example, if the ingestible device is designed to monitor the digestive system, then the ingestible device may be ingested by a subject. As the ingestible device travels through the living body, the ingestible device may receive first input indicative of an instruction to begin recording image data from a controller located outside the living body (step **1102**).

The ingestible device may cause the optical sensor to begin generating image data in response to the first input (step **1103**). Alternatively, the optical sensor could be configured to automatically begin generating image data after the ingestible device has been removed from its packaging, or after a mechanical switch accessible along the exterior surface of the ingestible device has been activated. In some embodiments, the ingestible device can be remotely activated by a source located outside the living body via RF signals, magnetic signals, optical signals, etc. For example, the optical sensor may begin generating image data responsive to determining that the ingestible device has been outside of the packaging for a certain amount of time (e.g., 3 minutes, 5 minutes, 10 minutes, etc.). As another example, the optical sensor may begin generating image data responsive to determining that the ingestible device has entered a particular in vivo environment.

The ingestible device can then wirelessly transmit at least some of the image data to a receiver using an antenna (step **1104**). For example, a processor may transmit the image data to a transceiver responsible for modulating the image data onto the antenna for transmission to the receiver. In some embodiments, the image data is transmitted in its original (i.e., raw) form. In other embodiments, the image data is transmitted in a processed form. For example, the processor may filter values from the image data, add metadata (e.g., specifying a location, time, or identifier associated with the living body), etc. As noted above, the receiver may be part of the controller or some other electronic device. For example, a medical professional may view the image data and control the ingestible device using a mobile workstation that is wirelessly connected to the ingestible device. As another example, a medical professional may view the image data on a tablet computer and control the ingestible device using a dedicated input device that is similar to controllers for video game consoles.

In some instances, the medical professional may wish to view a particular structure in the living body. Accordingly, the ingestible device may receive a second input indicative of an instruction to move so that the structure can be observed by the optical sensor (step **1105**). Said another way, the ingestible device may move so that the structure is located in a field of view (FoV) of the optical sensor. The ingestible device may move by altering its position and/or orientation. The ingestible device may determine the appropriate driving signal for each propulsion component based on the desired position and/or characteristics of the in vivo environment, such as viscosity, flow rate, temperature, etc. Once the ingestible device has reached the desired position, the ingestible device may automatically maintain its position until a predetermined interval of time expires or until an instruction to move to a new position is received from the controller.

The ingestible device can then cause at least one propulsor to be driven in response to the second input (step **1106**). In some embodiments, the propulsor(s) are driven based entirely on the second input. For example, if the second input is representative of an instruction to move forward, the propulsor(s) can be driven to achieve forward movement.

For embodiments of the ingestible device that are powered using an onboard battery, it is generally desirable to minimize battery discharge before the ingestible device is ready to be used in order to maximize the amount of power available during operation. To avoid battery drain during shipping and storage prior to deployment, the ingestible device may enter a low-power inactive state where current drawn from the battery is minimized or the battery is disconnected from other components (e.g., with a mechanical switch, a transistor such as a MOSFET, or some other means). To leave this state, the ingestible device may be activated by a sensor.

Some embodiments of the ingestible device employ a photosensor that prompts activation when light is detected. The photosensor may be configured to generate readings indicative of the level of visible, infrared, or ultraviolet light that is presently detectable. In these embodiments, the ingestible device may be shipped and stored in a substantially opaque package to prevent the photosensor from being activated inadvertently or prematurely. When the package is opened, the photosensor will be exposed to light and the ingestible device can be activated. Other embodiments of the ingestible device employ a low-power magnetic sensor that activates when the ingestible device is exposed to a magnetic field. Alternatively, the ingestible device may include a low-power magnetic sensor that activates when the ingestible device is not exposed to a magnetic field. For instance, a magnet may be included in the packaging so that the ingestible device is exposed to a magnetic field at all times while being shipped and stored. This embodiment has several advantages. First, there is minimal risk of premature activation since the packaging is likely to accompany the ingestible device until deployment is imminent. Second, the individual responsible for deploying the ingestible device does not need to introduce an activation signal such as a magnetic field. Other embodiments of the ingestible device may use a reed relay as a mechanical power switch to activate the ingestible device upon being exposed to a magnetic field. In embodiments where the ingestible device is activated by exposure to a magnetic field, a single- or multiple-use magnetic fixture could be used to facilitate activation by holding the magnet in the correct orientation with respect to the ingestible device. Other embodiments of the ingestible device may be activated by a mechanical element (e.g., a switch or button) that is sealed to prevent fluid ingress but is located along the exterior surface of the enclosure so as to be accessible.

As discussed above, the ingestible device may have built-in features, such as sensors, software, and the like, for performing self-diagnostic tests. Using these built-in features, health and performance functions of the ingestible device can be regularly tested. These built-in features can also help in debugging and exploring new operational regimes. Examples of self-diagnostic tests include checksum errors, software versioning, battery voltage, power draw per motor, tests of other major components, etc. Alternately or additionally, the camera may be commanded to generate a test image (e.g., of packaging) to be transmitted to a destination (e.g., the controller), where it may be compared to an expected reference image. Successful transmission of the test image would require the ingestible device be functioning properly. If the test image is not received or is not correct, it could signify a defect (e.g., in the ingestible device, communication channel, etc.) for which an alert may be generated that indicates that the ingestible device should not be deployed.

Communication Environment

FIG. **12** depicts an example of a communication environment **1200** that includes an ingestible device **1202** that is communicatively coupled to a controller **1204**. An operator can control the ingestible device **1202** using the controller **1204**. Moreover, the ingestible device **1202** can be configured to transmit data (e.g., image data or biometric data) to one or more electronic devices. Examples of electronic devices include monitors **1206**, computer servers **1208**, and mobile phones **1210**. The ingestible device **1202**, controller **1204**, and electronic device(s) may collectively be referred to as the "networked devices."

In some embodiments, the networked devices are connected to one another via point-to-point wireless connections as shown in FIG. **12**. For example, the ingestible device **1202** may be communicatively coupled to the controller **1204** via Bluetooth®, Near Field Communication (NFC), Wi-Fi® Direct (also referred to as "Wi-Fi P2P"), Zigbee®, another commercial point-to-point protocol, or a proprietary point-to-point protocol. In other embodiments, the networked devices are connected to one another via networks, such as personal area networks (PANs), local area networks (LANs), wide area networks (WANs), metropolitan area networks (MANs), cellular networks, or the Internet. For example, the ingestible device **1202** may be communicatively coupled to a monitor **1206** and a computer server **1208** via separate LoRa® communication channels.

The connections established between the networked devices may be bidirectional or unidirectional. For example, the controller **1204** may be permitted to transmit data to the ingestible device **1202** even though the ingestible device **1202** may be unable to transmit data to the controller **1204**. Similarly, the ingestible device **1202** may be permitted to transmit data to the electronic device(s) even though the electronic device(s) may be unable to transmit data to the ingestible device **1202**.

Embodiments of the communication environment **1200** may include some or all of the networked devices. For example, some embodiments of the communication environment **1200** include an ingestible device **1202** and a single device (e.g., a mobile phone, tablet computer, or mobile workstation) that serves as the controller and the electronic device on which image data is reviewed. As another example, some embodiments of the communication environment **1200** include an ingestible device **1202** and a computer server **1208** on which the image data is stored for subsequent review. In such embodiments, because the image data will be reviewed at some later point in time, the communication environment **1200** need not include a controller **1204**. As another example, some embodiments of the communication environment **1200** include a dedicated input device without display capabilities that serves as the controller **1204** and an electronic device, such as a tablet computer or a mobile phone, on which image data is reviewed. In such embodiments, the dedicated input device may be communicatively coupled to the ingestible device and/or the electronic device.

Since the ingestible device **1202** can operate in vivo, the close proximity to fluids, tissue, and the like may affect the electromagnetic operating characteristics of the antenna. To address this, the antenna may be designed and/or selected to minimize the effects of nearby materials having relative dielectric constants that are significantly different from free space. As an example, an embodiment could use a small loop antenna with one or more turns, which primarily interacts with magnetic field components in the near field, and is therefore less strongly affected by the proximity of high-dielectric materials. Alternatively, the antenna may be designed and/or selected to compensate for the effect of the fluid(s) inside the living body. As an example, an embodiment could use a straight, bent, curved, or meandered antenna (e.g., monopole antenna) where the effective electrical antenna length is between one-eighth and one-third of the transceiver operating wavelength when the ingestible device **1202** is surrounded by fluid or anatomy of the living body. For instance, an embodiment could use a monopole or "whip" antenna that is significantly shorter than a free-space quarter wavelength. While this antenna would not be tuned optimally in air, proximity to the high-dielectric fluid(s) may cause the antenna to behave electrically as if it were significantly longer and tuned properly to the frequency of interest. Such an approach also has the benefit of allowing the use of a significantly smaller antenna than would be optimal for operation in dry air. The mechanical structure of the antenna may be designed to conform to the enclosure of the ingestible device **1202**.

The antenna and transceiver circuitry may be designed such that a single antenna is used for both transmitting and receiving data. Alternatively, multiple antennas may be used. For example, different antennas may offer superior performance in certain orientations or fluid conditions, and the performance of each antenna may be monitored during operation in order to select the antenna with the highest performance at any given point in time. In embodiments that use wireless power transmission, the ingestible device **1202** may be configured to use a single antenna for both power and data transmission to eliminate the need for an additional antenna. Alternatively, different antennas or electromagnetically coupled structures may be used for power and data transmission, allowing each to be optimized for its respective task.

To allow multiple ingestible devices to operate within close proximity (e.g., multiple patients undergoing treatment in the same room or building), the communication channels discussed above may be established using a pairing feature. Pairing features may be employed to ensure that each ingestible device communicates with a single controller. To accomplish this, each ingestible device may be assigned a unique identification number during manufacturing. When a communication channel is established by an ingestible device, the ingestible device may transmit its identifier to establish whether the communication channel was established with the appropriate controller. Additionally or alternatively, the ingestible device may append the identifier (or a shortened/amended identifier) as a label to data packets to designate the appropriate controller. Accordingly, each controller may assume that data packets without the correct identifier are meant to be received by another controller and thus can be ignored. As part of this process, the ingestible device and corresponding controller may elect to switch to a different communication channel or frequency to avoid having to share time and bandwidth with other pairs of ingestible devices and controllers. The ingestible device and corresponding controller may elect to change communication frequency as needed during operation to avoid competing with interfering devices, a strategy known as "frequency hopping."

Processing System

FIG. **13** is a block diagram illustrating an example of a processing system **1300** in which at least some operations described herein can be implemented. Components of the processing system **1300** may be hosted on an ingestible device (e.g., ingestible device **100** of FIG. **1**).

The processing system **1300** may include a central processing unit ("processor") **1302**, main memory **1306**, non-volatile memory **1310**, wireless transceiver **1312**, input/output device **1318**, control device **1320**, drive unit **1322** including a storage medium **1324**, and signal generation device **1328** that are communicatively connected to a bus **1316**. The bus **1316** is illustrated as an abstraction that represents one or more physical buses and/or point-to-point connections that are connected by appropriate bridges, adapters, or controllers. The bus **1316**, therefore, can include a system bus, Peripheral Component Interconnect (PCI) bus, PCI-Express bus, HyperTransport bus, Industry Standard Architecture (ISA) bus, Small Computer System Interface (SCSI) bus, Universal Serial Bus (USB), Inter-Integrated Circuit (I^2C) bus, or bus compliant with Institute of Electrical and Electronics Engineers (IEEE) Standard 1394.

The processing system **1300** may share a similar computer processor architecture as that of a desktop computer, tablet computer, mobile phone, video game console, wearable electronic device (e.g., a watch or fitness tracker), network-connected ("smart") device (e.g., a television or home assistant device), augmented or virtual reality system (e.g., a head-mounted display), or another electronic device capable of executing a set of instructions (sequential or otherwise) that specify action(s) to be taken by the processing system **1300**.

While the main memory **1306**, non-volatile memory **1310**, and storage medium **1324** are shown to be a single medium, the terms "storage medium" and "machine-readable medium" should be taken to include a single medium or multiple media that stores one or more sets of instructions **1326**. The terms "storage medium" and "machine-readable medium" should also be taken to include any medium that is capable of storing, encoding, or carrying a set of instructions for execution by the processing system **1300**.

In general, the routines executed to implement the embodiments of the disclosure may be implemented as part of an operating system or a specific application, component, program, object, module, or sequence of instructions (collectively referred to as "computer programs"). The computer programs typically comprise instructions (e.g., instructions **1304**, **1308**, **1326**) set at various times in various memories and storage devices in an electronic device. When read and executed by the processor **1302**, the instructions cause the processing system **1300** to perform operations to execute various aspects of the present disclosure.

While embodiments have been described in the context of fully functioning electronic devices, those skilled in the art will appreciate that the various embodiments are capable of being distributed as a program product in a variety of forms. The present disclosure applies regardless of the particular type of machine- or computer-readable medium used to actually cause the distribution. Further examples of machine- and computer-readable media include recordable-type media such as volatile and non-volatile memory devices **1310**, removable disks, hard disk drives, optical disks (e.g., Compact Disk Read-Only Memory (CD-ROMS) and Digital Versatile Disks (DVDs)), cloud-based storage, and transmission-type media such as digital and analog communication links.

The wireless transceiver **1312** enables the processing system **1300** to mediate data in a network **1314** with an entity that is external to the processing system **1300** through any wireless communication protocol supported by the processing system **1300** and the external entity. The wireless transceiver **1312** can include, for example, an integrated circuit (e.g., enabling communication over Bluetooth or Wi-Fi), network adaptor card, or wireless network interface card.

The techniques introduced here can be implemented using software, firmware, hardware, or a combination of such forms. For example, aspects of the present disclosure may be implemented using special-purpose hardwired (i.e., non-programmable) circuitry in the form of application-specific integrated circuits (ASICs), programmable logic devices (PLDs), field-programmable gate arrays (FPGAs), and the like.

Remarks

The foregoing description of various embodiments has been provided for the purposes of illustration. It is not intended to be exhaustive or to limit the claimed subject matter to the precise forms disclosed. Many modifications and variations will be apparent to one skilled in the art. Embodiments were chosen and described in order to best describe the principles of the invention and its practical applications, thereby enabling those skilled in the relevant art to understand the claimed subject matter, the various embodiments, and the various modifications that are suited to the particular uses contemplated.

Although the Detailed Description describes various embodiments, the technology can be practiced in many ways no matter how detailed the Detailed Description appears. Embodiments may vary considerably in their implementation details, while still being encompassed by the specification. Particular terminology used when describing certain features or aspects of various embodiments should not be taken to imply that the terminology is being redefined herein to be restricted to any specific characteristics, features, or aspects of the technology with which that terminology is associated. In general, the terms used in the following claims should not be construed to limit the technology to the specific embodiments disclosed in the specification, unless those terms are explicitly defined herein. Accordingly, the actual scope of the technology encompasses not only the disclosed embodiments, but also all equivalent ways of practicing or implementing the embodiments.

The language used in the specification has been principally selected for readability and instructional purposes. It may not have been selected to delineate or circumscribe the subject matter. It is therefore intended that the scope of the technology be limited not by this Detailed Description, but rather by any claims that issue on an application based hereon. Accordingly, the disclosure of various embodiments is intended to be illustrative, but not limiting, of the scope of the technology as set forth in the following claims.

What is claimed is:

1. An ingestible device comprising:

a capsule having a central axis defined therethrough; and

four rotors arranged in a cross-type configuration such that rotors that are radially opposite each other relative to the central axis share a common chirality while rotors that are rotationally adjacent each other relative to the central axis have opposite chirality;

wherein each rotor of the four rotors is located in a different channel defined through the capsule; and

wherein each channel includes

an inlet through which fluid is drawn by the corresponding rotor, and

an outlet through which the fluid is discharged by the corresponding rotor.

2. The ingestible device of claim **1**, wherein each rotor of the four rotors has a fixed pitch.

3. The ingestible device of claim **1**, wherein the capsule includes a substantially cylindrical segment that is interconnected between a first rounded segment and a second rounded segment.

4. The ingestible device of claim **3**,

wherein the inlet of each channel is located in the substantially cylindrical segment of the capsule, and

wherein the outlet of each channel is located in the first rounded segment of the capsule.

5. The ingestible device of claim **1**, further comprising:

four motors configured to supply motive power to the four rotors,

wherein each motor of the four motors is responsible for independently driving a corresponding rotor of the four rotors.

6. The ingestible device of claim **1**,

wherein the inlet of each channel has a first diameter, and

wherein the outlet of each channel has a second diameter less than the first diameter.

7. The ingestible device of claim **1**, wherein the four rotors are arranged along a radial plane orthogonal to the central axis.

8. The ingestible device of claim **1**, wherein each rotor of the four rotors includes a single blade.

9. The ingestible device of claim **1**, wherein each rotor of the four rotors comprises a biocompatible material.

10. The ingestible device of claim **1**, wherein each rotor of the four rotors comprises a stainless steel alloy, a polymer, a fiber-reinforced polymer, or a combination thereof.

11. The ingestible device of claim **1**, wherein each rotor of the four rotors has a hydrophobic coating or a hydrophilic coating.

12. The ingestible device of claim **1**, wherein each channel further includes a filter through which the fluid drawn through the inlet by the corresponding rotor is passed to remove suspended objects that exceed a particular size.

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