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Modular "Plug-and-Play" Capsules for Multi-capsule Environment in the Gastrointestinal Tract

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Abstract— **The invention of wireless capsule endoscopy has opened new ways of diagnosing and treating diseases in the gastrointestinal tract. Current wireless capsules can perform simple operations such as imaging and data collection (like temperature, pressure, and pH) in the gastrointestinal tract. Researchers are now focusing on adding more sophisticated functions such as drug delivery, surgical clips/tags deployment, and tissue samples collection. The finite on-board power on these capsules is one of the factors that limits the functionalities of these wireless capsules. Thus multiple application-specific capsules would be needed to complete an endoscopic operation. This would give rise to a multi-capsule environment. Having a modular "plug-and-play" capsule design would facilitate doctors in configuring multiple application-specific capsules, e.g. tagging capsule, for use in the gastrointestinal tract. This multi-capsule environment also has the advantage of reducing power consumption through asymmetric multi-hop communication.**

I. Introduction

CURRENT endoscopies such as push endoscopies and colonoscopies have limitations. One of the limitations of these endoscopies is its accessibility. The push endoscope (inserted via the esophagus) can only access up to the proximal end of the small intestine. On the other hand, the colonoscope (inserted via the anus) can only access up to the caecum. This means that a section of the small intestine is still not accessible by these endoscopies [1].

With the introduction of the wireless capsule endoscopy in 2000 [1], this limitation has been removed. Wireless capsule endoscope (with its on-board camera) can capture images of the inside of the gastrointestinal tract as it moves along the gastrointestinal tract under the action of peristalsis. Current capsules can also carry sensors for collecting data (like temperature, pressure, and pH) in the gastrointestinal tract [2].

Research is currently ongoing to improve and expand the capabilities of these wireless capsules. These include enabling wireless capsules to deliver drugs [3], to deploy surgical clips/tags [4,5], to collect tissue samples (biopsies), and to move along the gastrointestinal tract without the aid of peristalsis [6,7].

However, attempts to incorporate these capabilities into the wireless capsules have encountered problems. One of these problems is the limited power on board the wireless capsules. The power stored in the on-board batteries was insufficient for these wireless capsules to complete their operations in the gastrointestinal tract. For example, in about 15% of the cases, the power in the image-capturing capsules expired even before these capsules reach the caecum [8]. As such, more sophisticated operations such as drug delivery, surgical clips/tags deployment, tissue samples collection, and locomotion would require more power for their successful operations.

In this article, we introduced the modular "plug-and-play" capsule design which could facilitate doctors in configuring the required application-specific capsules. Section III discussed the tagging mechanism used for deployment of surgical clips/tags. Section IV discusses a novel asymmetric multi-hop communication for reducing power consumption of capsules in a multi-capsule environment.

II. Modular Capsule Design

AN endoscopic operation may require more than one task to complete. For example, the operation to deploy surgical clips to a target site in the gastrointestinal tract may require two tasks working cooperatively, e.g. one task is to provide visual input and another task is to deploy surgical clip to the target site. Due to the power limitation mentioned earlier, each capsule at present could only carry out one task. As such, one capsule with camera could provide visual input whereas another capsule with tagging mechanism could deploy the surgical clip. Thus, we propose a multi-capsule environment in which multiple application-specific capsules work together to achieve a specific objective.

In such a multi-capsule environment, application-specific capsules deployed could be of several types. For example, there could be capsules for measuring temperature, pressure, and pH; another for capturing images and delivering drugs; yet another for deploying surgical clips/tags and collecting tissue samples. Each of these different applications generally

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requires a dedicated and application-specific capsule.

Even though these application-specific capsules perform different functions, they have common components: system controller, power supply, transceiver, and antenna as shown in Figure 1. As such, a standard base capsule (called the Standard Module Capsule) could be constructed to incorporate all these components into a capsule casing.

Similarly, components for specific applications could also be constructed into application-specific modules. For example, components for image-capturing application could

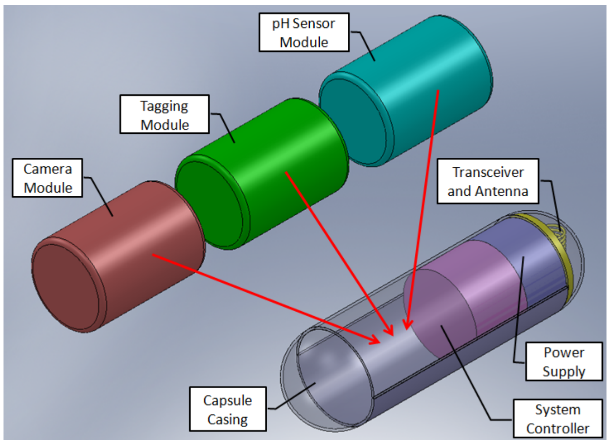

Fig. 1. The modular "plug-and-play" capsule design consists of the Standard Module Capsule and the application-specific modules. The Standard Module Capsule consists of the system controller, power supply, transceiver, and antenna constructed into a capsule casing. The application-specific modules (Camera Module, Tagging Module, and pH Sensor Module) could be plugged (as shown by the arrows) into the allocated space in the Standard Module Capsule to form the required application-specific capsule.

be constructed into a Camera Module, for tagging application into a Tagging Module, and for pH measurement into a pH Sensor Module as shown in Figure 1.

These Camera Module, Tagging Module, or pH Sensor Module could be plugged into the Standard Capsule Module to form the required application-specific capsules. This "plug-and-play" feature offers two advantages. Firstly, it could facilitate doctors to rapidly configure multiple application-specific capsules (which can be swallowed into the body over a period of time) to form a multi-capsule network in the gastrointestinal tract. Secondly, having one standard module (Standard Module Capsule) for all application-specific capsules could save design and fabrication costs. For example, there is no need to have ten different system controllers, power supplies, transceivers, and antennae just for ten different application-specific capsules.

Another aspect of the multi-capsule environment is the need for inter-capsule communication and capsule-base station communication. This is because capsules sometimes need to synchronise with one another when performing cooperative work. One such cooperative work is the relaying of images from capsule to capsule back to the base station. This route saves power consumption and would be discussed in Section IV.

III. Tagging Mechanism

An example of a modular "plug-and-play" capsule being developed is the tagging therapeutic capsule for deployment of surgical clips/tags. Deployment of surgical clips/tags at tumour sites in the gastrointestinal tract helps doctors to locate these sites again later for the purpose of surgical removal of the tumours or for radiotherapy [5]. Thus, endoscopic marking using surgical clips/tags is an important part of therapy.

As mentioned earlier, current endoscopes such as push endoscopes and colonoscopes are not able to access the whole length of the small intestine [1]. Thus, these devices are not able to deploy surgical clips/tags at tumour sites located in the inaccessible part of the small intestine.

This limitation could be overcome with wireless capsules which are equipped with tagging capabilities as wireless capsules can move through the entire length of the intestine.

A tagging mechanism developed for the wireless capsule was discussed here. The device could be used to deploy a small clip into the gastrointestinal wall at the tumour site. The embedded clip could then be located again visually or with the aid of X-ray. Figure 2 shows the idea of a capsule (with tagging mechanism) deploying a surgical clip, e.g. a metal clip, into the wall of the gastrointestinal tract.

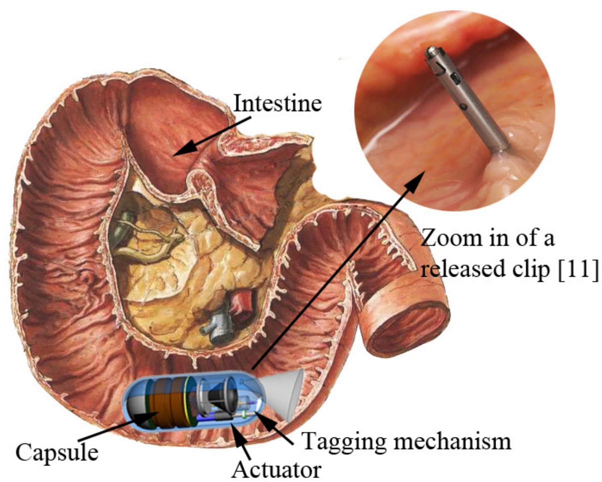

Fig. 2. Idea of tagging capsule deploying a surgical clip. When the capsule arrived at the target site in the gastrointestinal tract, the doctor would trigger the tagging device, which would eject the clip into the gastrointestinal wall. Visual input could be provided by a second capsule equipped with a camera (not shown).

Design

Figure 3 shows the design of the miniature tagging mechanism. This device measures 2 mm in diameter and 6 mm in length. A titanium needle of 0.5 mm in diameter and 1 mm in length was used as the tag.

The spring was held in a compressed state (State A in Figure 3) by a high tensile strength nylon thread which looped over the latch on the piston (Figure 3). A microheater was placed at the base of the tagging device and in contact with the nylon thread.

When the capsule arrived at the target site in the gastrointestinal tract, the doctor would trigger the tagging device which would eject a tag which then embed itself into the gastrointestinal wall. Visual input could be provided by a second capsule equipped with a camera.

Triggering the tagging device would cause the microheater to heat up rapidly. The heat generated would soften and break the nylon thread, thereby releasing the piston. The rapidly advancing piston in turn ejects the tag. The relative mass of the piston and the spring load would give the piston a high acceleration, resulting in a faster tag velocity.

The tagging mechanism could later be modified for delivering drugs to specific target sites on the gastrointestinal tract. The tag could contain a small reservoir of drug of the required dosage which could be released into the gastrointestinal tract.

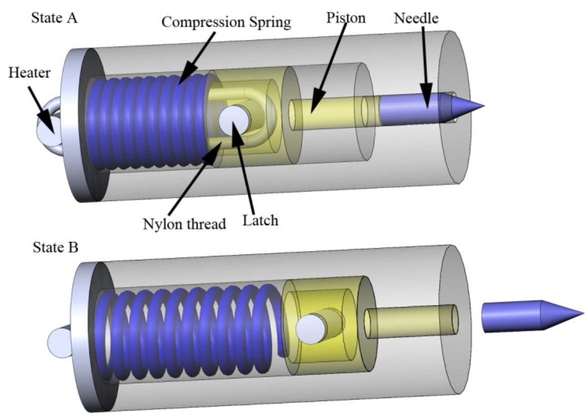

Fig. 3. Tagging mechanism. There are two states: State A (holding) and State B (firing). Triggering the tagging device would cause the heater to heat up rapidly. The heat generated would soften and break the nylon thread, thereby releasing the piston. The rapidly advancing piston in turn ejects the tag. The relative mass of the piston and the spring load would give the piston a high acceleration, resulting in a faster tag velocity.

IV. Asymmetric Multi-Hop Communication

In multi-capsule environment, each capsule need not be "overloaded" with many functionalities like in the single-capsule environment. Each capsule in a multi-capsule environment could be dedicated to performing only one function, e.g. one capsule for imaging, one capsule for tagging, and one capsule for collecting tissue samples. These application-specific capsules could cooperate with one another through inter-capsule communication. Several battery-carrying power capsules could also come together to form a power supply chain [9], for supplying power to the application-specific capsules. Besides these, multi-capsules could form a multi-hop communication network to reduce its power consumption.

It is known that multi-hop communication though the air could save power consumption compared with single-hop communication. For *in-vivo* wireless communication, because of the huge signal attenuation by body tissues, multi-hop communication would be more meaningful.

There are three communication topologies in which the capsules in a multi-capsule environment could communicate with the base station: centralized topology, distributed topology, and asymmetric link topology [10].

A. Centralized Topology

In the centralized topology, as shown in Figure 4, each capsule communicates with the base station. This is the type of communication used in WLAN. Uplink and downlink of data between capsules and base station follows the same routes. Body tissues between the capsules and the base station attenuate the signals. As such this topology is not suitable for multi-capsule environment as the amount of power loss is significant.

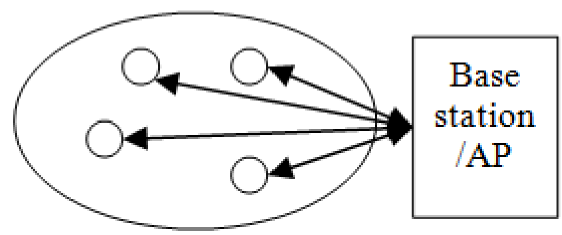

Fig. 4. Central Topology. In the centralized topology, each capsule communicates with the base station. Uplink and downlink of data between capsules and base station follows the same routes.

B. Distributed Topology

The multi-capsule environment has similar properties to the wireless sensor network, as both have limited power resources and the need to operate during mobility. Using multi-hop routing in a distributed topology network, as shown in Figure 5, could reduce power consumption significantly. In multi-hop routing, each capsule relays the data packets to the next capsule until the packets finally reach the router. Algorithms could be designed such that the route taken would be the one with the lowest power loss.

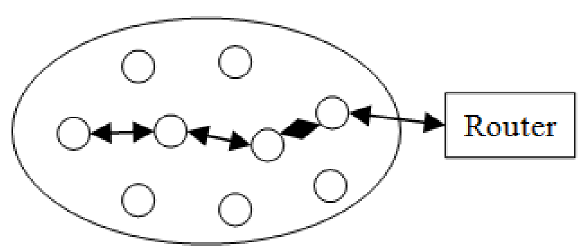

Fig. 5. Distributed Topology. In distributed topology, each capsule relays the data packets to the next capsule until the packets finally reach the router. Algorithms could be designed such that the route taken would be the one with the lowest power loss.

C. Asymmetric Link Topology

The power of the capsules is limited whereas the power of the base station is unlimited. As such, it is reasonable to propagate signals from the base station to all the capsules directly. However, signals from the capsules should be propagated via multi-hop routing to the base station, in order to reduce power consumption. The different routes taken during uplink and downlink form an asymmetric link topology as shown in Figure 6. This novel asymmetric multi-hop communication achieved lower power consumption as well as lower delay performance.

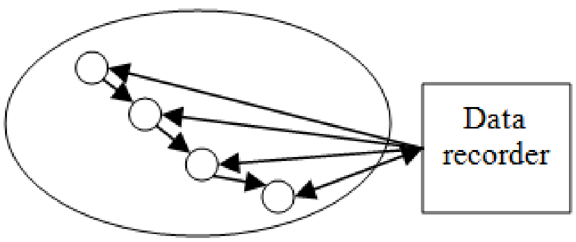

Fig. 6. Asymmetric Link Topology. In asymmetric link topology, signals were propagated from the base station to all the capsules directly. However, signals from the capsules were propagated via multi-hop routing to the base station. This asymmetric uplink and downlink multi-hop link topology achieved lower power consumption as well as lower delay performance.

V. Conclusion

IN this article, the modular "plug-and-play" capsule was introduced that could facilitate the construction of a multi-capsule environment in the gastrointestinal tract. The modular capsule design could also save design and fabrication costs.

A design of a tagging mechanism for endoscopic marking was discussed which would be modularised into an application-specific module. The possibility of extending this mechanism to drug delivery (using a tag with drug reservoir) was also highlighted.

Problem of insufficient power experienced in capsules was discussed and a novel asymmetric multi-hop communication network which would reduce power consumption was discussed.

Future work will focus on developing further the modular capsule design, the tagging mechanism, a suitable MAC protocol, and a routing protocol for the asymmetric link topology.

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