Endoscopy: Evolution and Future Directions with TRIZ

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Abstract

An endoscope is an instrument used to examine the interior of a hollow organ or cavity of the body, typically consisting of a rigid or flexible tube, a light delivery system, a camera to capture images, an image transmission system and additional channels to carry medical instruments or manipulators. Endoscopy technology has evolved over the years, both structurally and functionally, attempting to reach deeper into the complex contours of the human body. Rigid endoscopes evolved into flexible endoscopes and then further into the latest capsule endoscopes. Advancements in other technology areas such as illumination, imaging, microprocessors and communication have played a significant role in this evolution.

This paper uses the TRIZ laws of system evolution to analyze this evolution, identify patterns and to suggest potential future directions of evolution of endoscopy technology.

2 Introduction

2.1.1 Endoscopic Functions

The earliest known endoscope apparatus, the *Lichtleiter,* used a candle as the light source, a set of metal tubes (of different sizes for different body cavities) to direct light into the body and a peephole to view the internals. There are primarily three technology pillars of endoscopy:

1. Accessibility – ability to reach a specific location inside the human body
2. Illumination – ability to create an environment where high quality images can be captured
3. Imaging – ability to capture images that are suitable for diagnosis

The above three technology pillars enable a multitude of functions:

1. Primary function - Examination (and information for diagnosis)
2. Secondary (add-on) functions
    a. Tumor removal
    b. Tissue sampling
    c. Drug administration

The three technology pillars (sub-systems) of endoscopy are by no means exclusive to endoscopy – these sub-systems serve numerous other systems. For example, the combination of accessibility, illumination and imaging technologies are applicable to archaeological and geological contexts as well. Individually, they serve a vast super system of applications. Similarly, the sub-systems of these technology pillars such as semiconductors, microprocessors, light emission, flexible materials etc. have myriad other applications. All of these super systems and sub systems have contributed to the evolution of the technology pillars and in turn to the evolution of endoscopy as a whole.

2.1.2 TRIZ Laws and Lines of System Evolution

As part of TRIZ, various laws, lines and stages of technology evolution have been identified. It has been proposed (and observed) that technical systems do not evolve randomly; they follow certain laws and patterns. The laws and lines of system evolution are as follows:

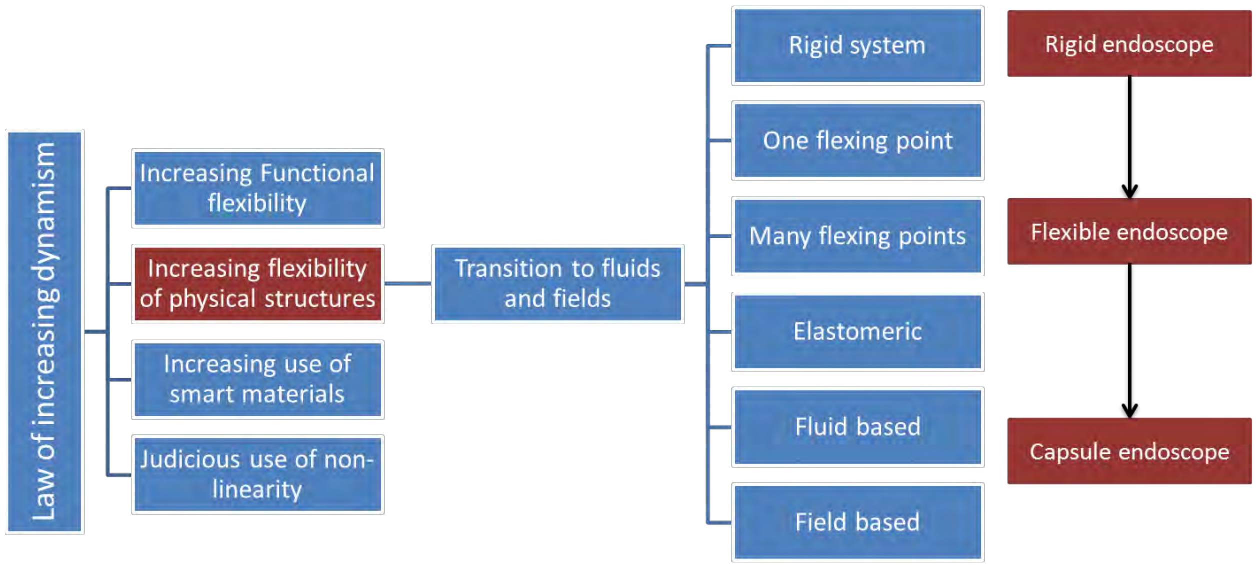
- Law of Increasing Ideality of Systems
- Law of Non-uniform Evolution of Sub-systems
- Law of Increasing dynamism
    - Line: Increasing functional flexibility
        - Sub-line: Transition to continuously variable systems
        - Sub-line: Transition to active adaptive systems
        - Sub-line: Transition to self-adapting systems
        - Sub-line: Transition to forward sensing systems
    - Line: Increasing flexibility of physical structures
        - Sub-line: Transition to fluids and fields
        - Sub-line: Increasing fragmentation
    - Line: Increasing use of smart materials
    - Line: Transition to non-linear systems
- Law of Transition to Higher Level Systems
    - Line: Increasing number of systems (mono-bi-poly)
    - Line: Increasing diversity of components
    - Line: Convolution

    - Line: Increasing non-uniformity of materials
- Law of Transition to micro-level
    - Line: Transition to micro-level
- Law of Completeness
    - Line: Completion
- Law of Shortening of Energy Flow Path
    - Line: Reduction in number of energy transformation stages
    - Line: Proliferation of easier to control energy forms
- Law of Increasing controllability
- Law of Harmonization of rhythms
    - Line: Chrono-kinematics
        - Sub-line: Two or more simultaneously operating systems
        - Sub-line: Transition to peak mode
        - Sub-line: Transition to preliminary action

2.1.3 Broad Endoscope Evolution Trend

In retrospect, we know now that the primary line of evolution of endoscopes has been the line of increasing flexibility of physical structures. This line indicates that rigid tubes will invariably evolve into flexible tubes with one or more flexing points, then elastomeric structures, followed by fluid-based and field-based structures. Endoscopes seem to have taken a similar path, over the last two centuries. This is in line with what we would expect from the need for accessibility or reach. However, in the case of endoscopes, this is not a stand-alone evolution line. Other sub-systems like illumination and imaging, as we shall see, had to evolve on other lines of evolution in order to enable the endoscopic tube to transition from rigid system to fluid and field based systems.

Figure 1. Endoscope Evolution - Line of Increasing Flexibility of Physical Structures



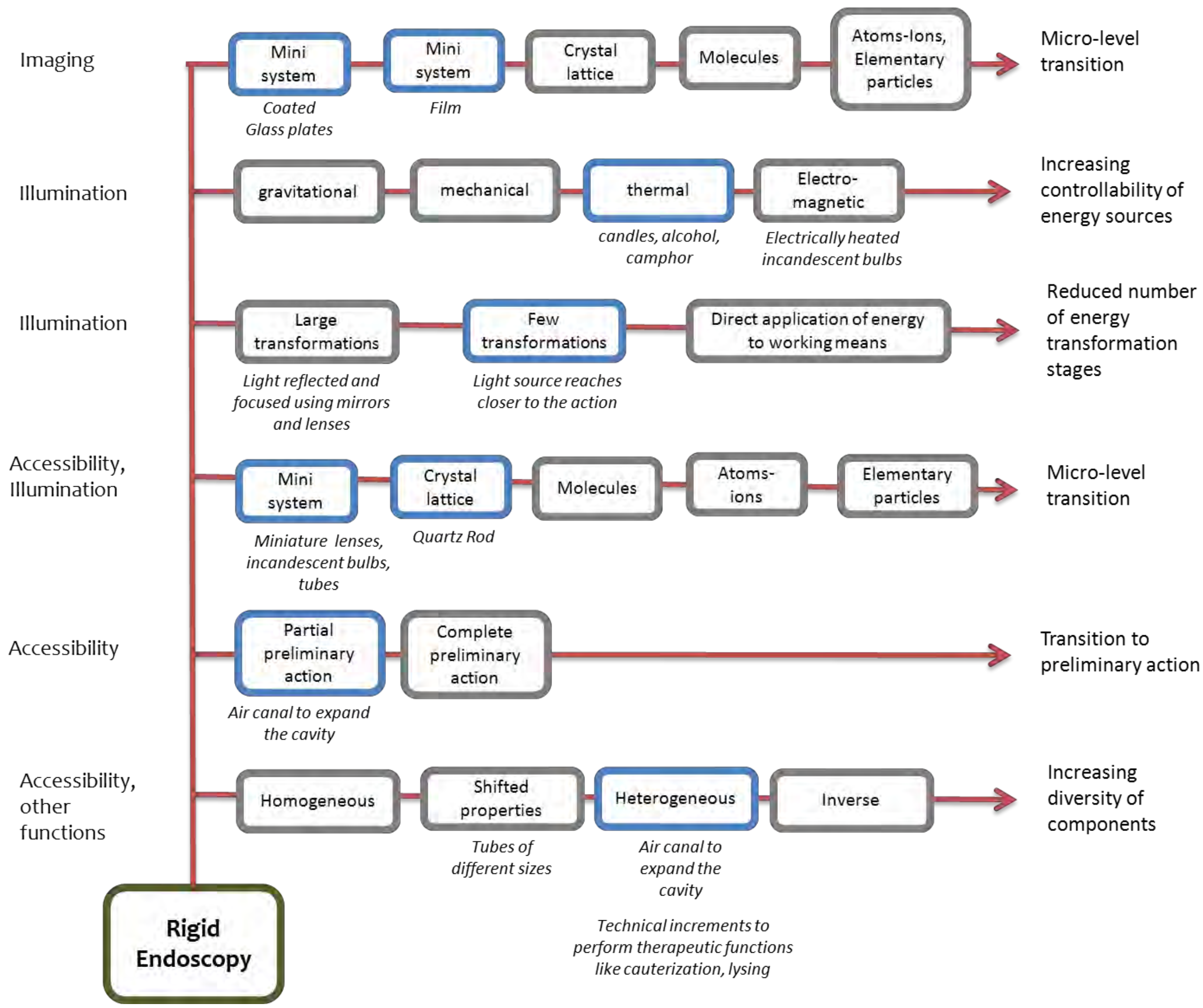
3 Rigid Endoscopy

Right through the nineteenth century, rigid tube based endoscopes were in use. Illumination was the major issue. Mirrors and lenses were used for directing and focusing light respectively, but with very incremental improvement in illumination. The light source itself was external to begin with; regular "heat-based" light sources such as candles, alcohol, turpentine, camphor etc. were experimented with. It was only after electrically heated light sources came into the picture that miniaturization or transition to the micro-level was made possible. With miniaturization, it was now possible to carry a light source such as electrically heated water-cooled platinum wire or a miniature electrically heated incandescent bulb into the cavity for radically improved illumination. Of course, carrying heat-based light into the body also carried with it the complications of burns, a problem that wasn‟t resolved till the advent of "cold light". Meanwhile, light transmission technology was also evolving. Quartz rod transmission significantly improved the efficiency of light transmission, and thereby illumination intensity. This transition, as will become obvious later, was also an instance of transition to the micro-level.

Simultaneously, the ability to capture images of the internal body cavities was emerging. Starting from glass plates coated with photographic material, the imaging system started to transition to the micro-level with the advent of photographic film. The first swallowable film based camera (connected to a rubber tube) hinted at the possibility of separation of light transmission and image viewing functions. The endoscope could go in and capture images for later viewing.

In addition to an increasing number of systems (mono-bi-poly for mirrors, lenses, tubes etc.), the rigid endoscope also saw an increasing diversity of systems in the form of an air canal to inflate the cavity and increase the scope of view as well as to enable viewing collapsed body cavities (a good example of movement on the line of preliminary action as well), specialized tweaks to the apparatus to enable therapeutic procedures like lysing and cauterization using chemicals etc.

Figure 2. Rigid Endoscopy - Evolution Tree



4 Flexible Endoscopy

The first flexible endoscopes were semi flexible ones - they had a flexible lower third (towards the tip) and a rigid upper part. This was necessitated by a fundamental contradiction – more flexible the tube, more complex the light guiding sub-systems of the apparatus. With a rigid tube, light guiding was easier, but the endoscope couldn't reach very far. Even with the possibility of carrying a miniaturized light source into the cavity for illumination, light still had to be reflected out for viewing. Endoscope design, predictably, tried to optimize between accessibility and illumination/viewing. The flexible part of the endoscope could bend up to an angle of 45 degrees, beyond which image (light) transmission capability would be lost.

On the imaging side, a miniature camera installed at the tip of a flexible tube was introduced. In addition to the camera, the apparatus contained a mini light globe and a manually operated flash. The flexible tube also contained a wire mechanism to wind the photographic film. However, this apparatus was "blind" – real time diagnosis or other endoscopic procedures could not be performed. This was therefore, the end of the road for the miniature camera and miniature bulb, for the time being.

For real time endoscopy to evolve further, light transmission and focusing systems had to evolve. This evolution came in the shape of fiber optics technology (optical fibers can be bent without any impact on light transmission) and the rod-lens system (that improved illumination by more than 80%). These sub systems (mirrors and lenses) were transitioning to the micro-level and convolving.

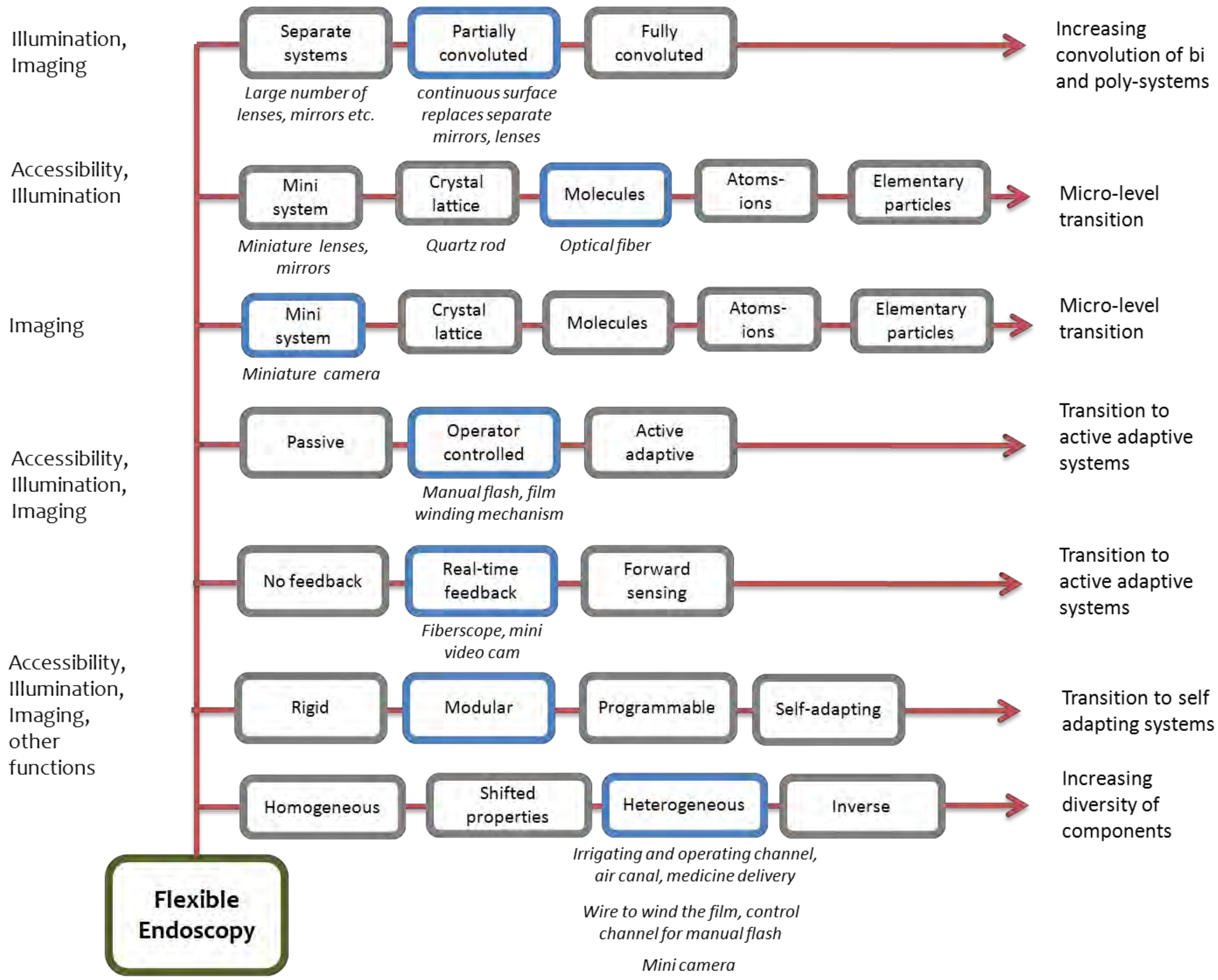
Interestingly with the advent of fiber optics, it was no longer critical to carry the light source into the body, an external light source was sufficient. This was a temporary reversal of the trend of the energy source becoming smaller and moving closer to the action area.

Two laws seem to be assuming increasing importance in the evolution – Law of Transition to Higher Level System, specifically the line of increasing diversity of components and the Law of Increasing Dynamism, specifically the lines of increasing functional flexibility.

A heterogeneous combination of the miniature camera and the optical fiber based light transmission (both in and out) created the fiberscope, "a camera with an eye", enabling real-time feedback. Soon enough, a miniature video camera was also introduced. The endoscope had now morphed into a flexible conduit for different kinds of flexible channels (illumination, imaging, control channels, irrigation, medicine delivery, other therapeutic functions) and with several miniature devices at the tip of the endoscope. The endoscope and its various functions were moving from passive to operator-controlled mode of operation. Also apparent was the increasing modularity, a first step towards a self-adapting system.

Despite significant breakthroughs and improvements in flexible endoscopy as outlined above, tube based endoscopes were not sufficiently flexible to reach certain complex portions of the human body, deep into the small intestine for instance. This necessitated the next wave of system evolution, culminating in capsule endoscopy.

Figure 3. Flexible Endoscopy - Evolution Tree



5 Capsule endoscopy

The next phase of evolution of the flexible endoscope along the line of transition to fluids and fields was the fluid/ field stage. Now, this needed the umbilical cord represented by the flexible tube to be cut. In turn this meant that all endoscopy sub-systems would have to be consolidated at the tool tip and work in a standalone manner.

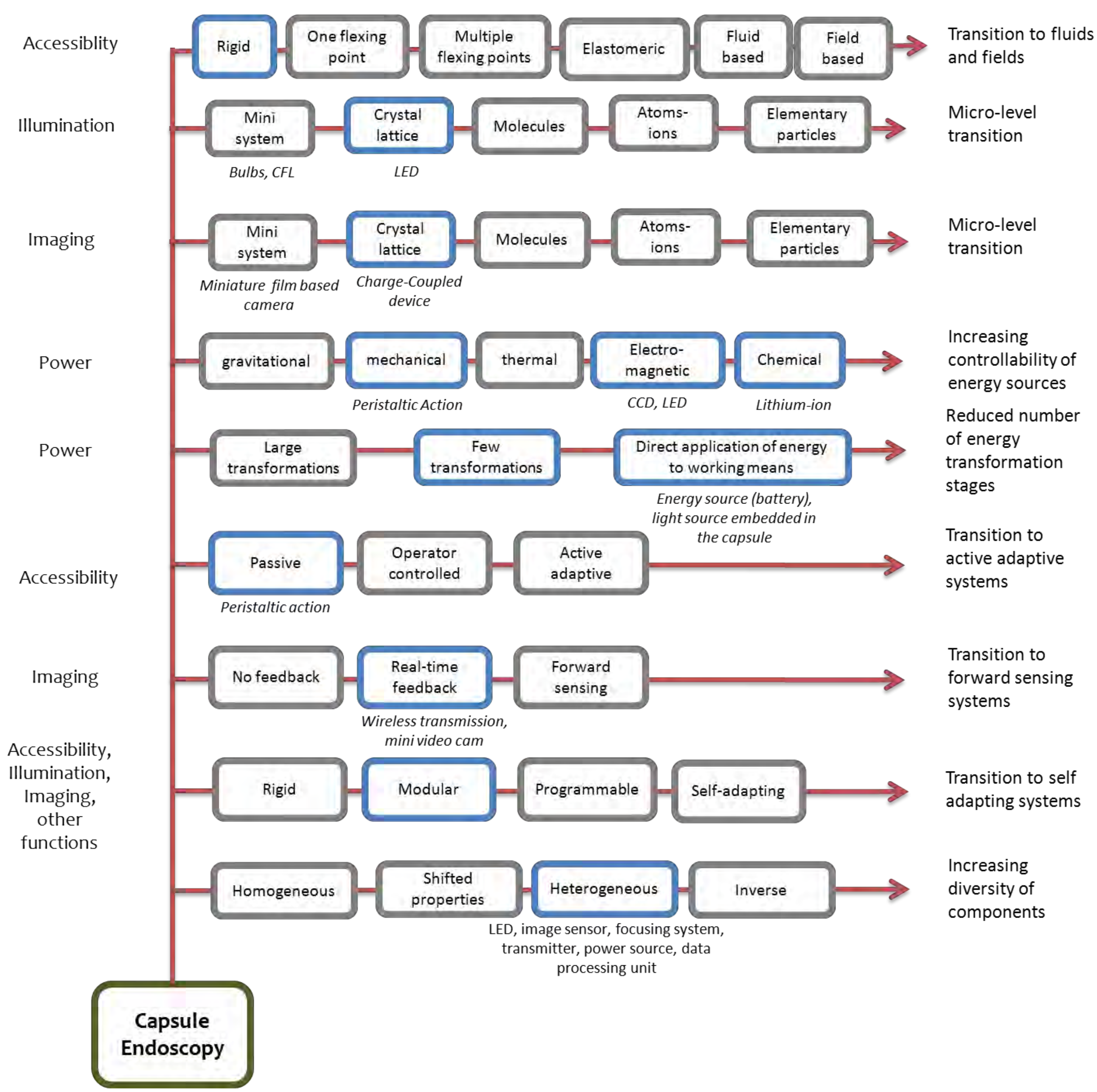
Irrevocably, all sub systems have moved towards this objective. The driving force behind this movement was the evolution of the semiconductor and electronics industry and then as a consequence digital technology, computer science and data processing.

Lighting systems evolved from incandescent light to “cold light” in the form of fluorescent lamps and then on to light emitting diodes (LEDs). The continuous transition to micro-level is clearly seen. This meant that a miniature cold light source could be positioned at the tool tip. Furthermore, the LED also lends itself well to controlled and flexible lighting, along the line of increasing controllability of energy sources and has low power consumption attributes.

The transition to micro level is also seen on the imaging side, with the advent of the charge coupled device (CCD). It was now possible with CCD based miniature cameras to convert image information to electrical signals, suitable for efficient transmission and processing. Images and videos could now be transmitted over wires or using wireless communication technologies instead of optical fibers. With digital technology, information storage, transmission and processing efficiencies increased manifold. All of this contributed to a significant increase in functional flexibility.

Battery technology had also transitioned to the micro level with the introduction of light weight Lithium-ion batteries with high energy-to-weight ratio.

Figure 4. Capsule Endoscopy - Evolution Tree, Past and Present



Put together, these sub-systems were now ready to work in stand-alone "wireless mode" and small enough to fit into a capsule that could be swallowed like a regular medicinal capsule, automatically pushed through the gastro-intestinal tract by means of peristaltic action. The capsule, with all sub-systems embedded within, embodies the application of energy directly to the working means with minimum energy losses during transmission.

Figure 5. An industrial capsule endoscope

Some of the commercial capsule endoscopes include:

i) PillCam(R) marketed in the United States by InScope, a business division of Johnson & Johnson subsidiary Ethicon Endo-Surgery

ii) EndoCapsule produced by Olympus Corporation (EP 2163206 (A1)).

6 Further Evolution

As we have seen, in terms of flexibility of physical structure, the endoscope has completed one cycle of what may be called an evolution spiral. It is now at pretty much the beginning of a second cycle and therefore at the inception stage of its S-curve. Clearly, many of the other operator controlled subsystems for diagnostic and therapeutic functions such as irrigation, drug delivery, cauterization etc. have yet to catch up to fit into the capsule paradigm. They will no doubt, in due time, transition to the micro-level and add to the diversity of heterogeneous capsule components.

The following laws and lines of action have seen the most evolution activity thus far – we can expect the evolution to continue in the near future as well.

6.1 Law of Increasing Dynamism

6.1.1 Line of Increasing flexibility of physical structures

6.1.1.1 Transition to fluids and fields

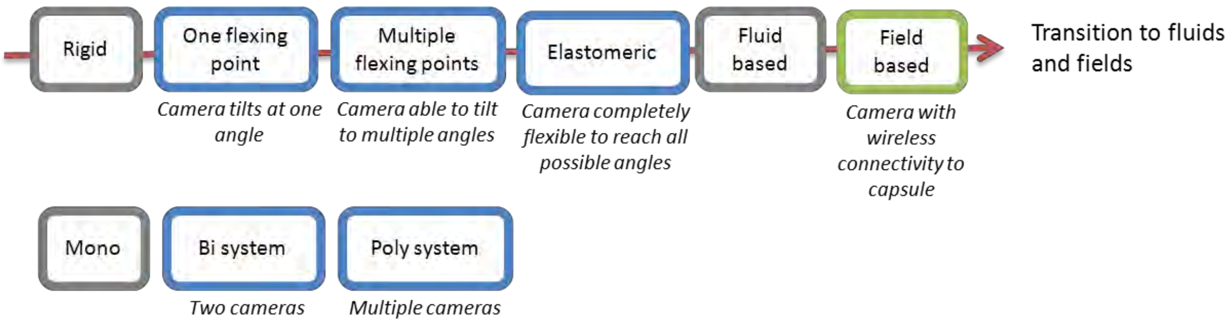
We are already seeing evidence of the rigid capsule adding one or more flexing points for improved accessibility, illumination and imaging. For example, the rigid bi-camera capsule system soon evolved into a s**ystem with one flexing point** with two distinct camera housings linked through a flexible connection (U.S. Patent Publication No. 2003/0023150).

We also have s**ystems with many flexing points and elastomeric systems** that allow the camera to be tilted in all possible directions to acquire **separate** images (U.S. Patent Publication No. 2005/004358).

Moving along the line of transition to fluids and fields, it is likely that

- the capsule system will split into multiple systems connected together through wireless communication and remote control mechanisms
- These could be multiple smaller capsules (the mono-bi-poly line) or specific capsule sub-systems like imaging or lighting

Figure 6. Transition to fluids and fields



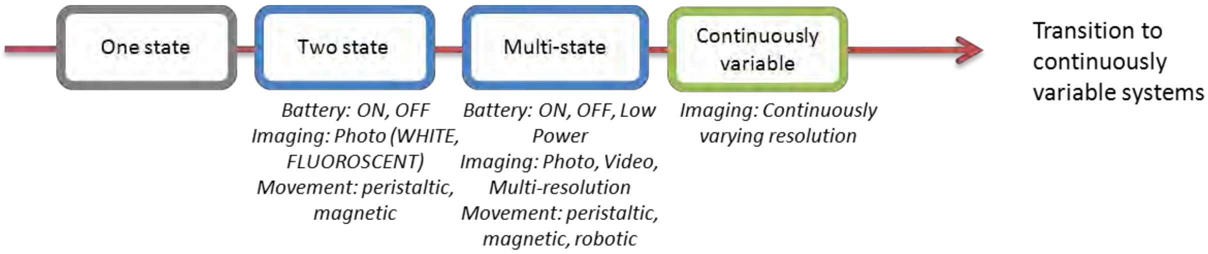
6.1.2 Line of increasing functional flexibility

6.1.2.1 Continuously variable

Capsule endoscopes started currently operate in a single state (ON mode) from injection to ejection. Each of the sub-systems of the capsule can evolve to multi-state and continuously variable system. For example,

- the battery can remain switched off or in standby or low power state till it reaches the relevant location
- the camera can operate in multiple states, starting off in photo mode and switching to video mode when required.
- imaging can be based on white light or fluorescent lighting
- Illumination and image resolution can be continuously variable depending on ambient conditions and proximity to the location of interest (*the first capsule endoscopes would capture as many images as possible from injection to ejection; sorting out the relevant images was a time consuming and laborious (manual) task. Patent Application US2009240108 (A1) describes a system with a judging device to control the imaging operations by switching the camera in a special mode from normal mode to take more and magnified pictures of interested lesion area)*
- the capsule can travel in multiple modes, through peristaltic action initially and then controlled externally by a magnetic field or internal electromechanical action (robotic) using grippers etc.

Figure 7. Transition to continuously variable systems



6.1.2.2 Active adaptive

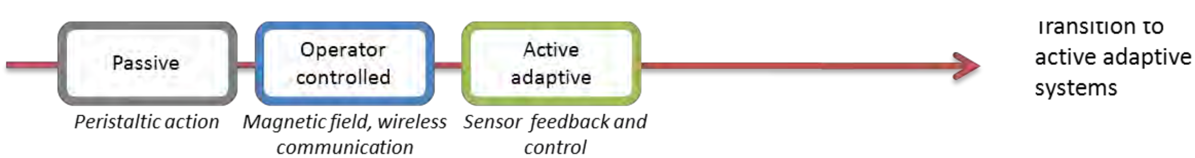
With the recent advances in wireless communication capability it is likely in the immediate future that all the sub systems of the capsule endoscope can be **controlled externally by an operator**. For example,

- the capsule movement can be controlled using a magnetic field or other wireless communication methods like telemetry (*Patent CN101011234 (A) - when guided movement using in vitro wireless remote control, and real-time information transmission functions were introduced into a system, the direction of the capsule could be adjusted to complete the motion or stop the motion*)
- camera movement can be controlled and acquisition region can be defined or changed by the doctor

The movement to **active adaptive** systems requires the capsule to have some kind of intelligence or processing capability embedded within. For example,

- more detailed images captured only in the area of interest using sensors to judge the environment (*US2009240108(A1)*). This is also indicative of movement on the lines of transition **to forward sensing** (real-time feedback) and **self-adapting** systems.
- ability to sense the environment conditions (e.g. pH levels, concentration of enzymes etc.) and determine the course of action

Figure 8. Transition to active adaptive systems



6.1.2.3 Self adapting

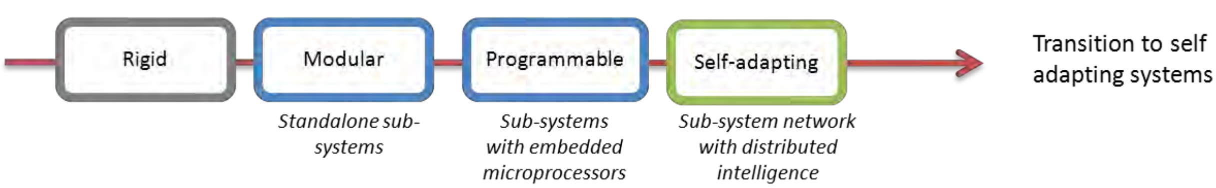
Capsule endoscopes are already somewhat **modular** considering that all the subsystems are standalone systems housed in a common capsule. Further modularity can be achieved by ensuring that the components can be replaced or removed without impacting the working of other systems.

It is also likely that each of the sub-systems will have an embedded microprocessor so that it can be individually **programmed**. For example,

- The illumination system can have a microprocessor to choose the specific light wavelengths, illumination intensity etc.
- The Power system can have a microprocessor to control the power modes, switching to redundant power sources etc.
- The Imaging system can have a microprocessor to control camera movement, imaging frequency, imaging resolution, communication between multiple imaging systems etc.
- A central capsule microprocessor could control the other sub-system microprocessors

Another aspect of **programmability** is the variation in functionality of different types of endoscopes depending on the body cavity or region to be explored. Historically, we have had specialized endoscopes for the esophagus, the gastric tract, the small intestine etc. With the capsule endoscope, we now have the possibility of a convolution of systems; a single endoscope can be programmed to perform specialized functions depending on the environment. A programmed endoscope would, by design, work in a customized manner for a pre-determined set of environment conditions.

Figure 9. Transition to self-adapting systems



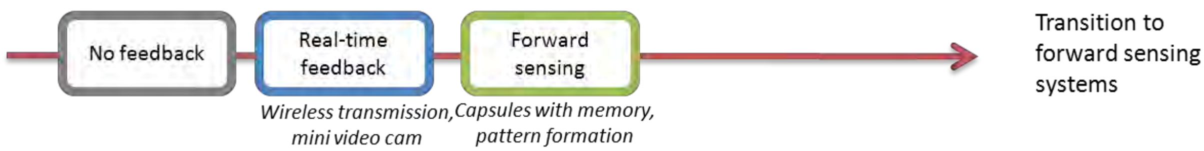
Further down the line, **self-adapting** endoscopes would be able to adapt themselves intelligently to any environment, including conditions that are previously unknown. This includes the possibility of distributed intelligent sub-systems (imaging, illumination, accessibility etc.) working in a networked configuration such as *hub and spoke* or *swarm* to change the shape, size, configuration and capability of the capsule based on the environment conditions. This would also bring into play the **Law of Harmonization of Rhythms**, where functions are distributed among **multiple simultaneously operating sources**.

6.1.2.4 *Forward sensing*

As of now, capsule endoscopes provide **real time feedback** through images and videos. We have also anticipated earlier that each of the endoscope subsystems will work in active adaptive mode through some specific real time feedback mechanism suitable for that sub-system. For example,

- Illumination and imaging systems will have sensors to detect ambient illumination, shape of cavity, contents etc.
- The Accessibility system will detect cavity shape, size etc.

Figure 10. Transition to forward sensing systems



Capsules with memory (external or internal) can help the system to transition to **forward sensing** mode. A database of information collected over multiple capsule traversals can help track the advancement of a lesion or a constriction and determine patterns in the evolution of different kinds of problems. Problems can be detected earlier.

6.2 Law of Transition to Higher Level

6.2.1 Line of increasing number of systems

There is a likelihood of **mono-bi-poly** transition. For example, multiple cameras and light sources might be useful in covering a larger three dimensional space for imaging purposes. Original capsule endoscopy possessed one camera to diagnose pathological changes of the small bowel. This fixed predetermined acquisition direction led to diagnostic errors, since the images were taken before the distension of the particular part of the bowel. As the capsule moved forward, lesions which would have occulted in the mucosal folds might become recognizable. This logic led to the development of **bi-system** cameras attached at the opposite end of the capsule (U.S. Patent Publication No. 2002/0109774) to capture a bidirectional view. Revisiting the intestinal surfaces enhanced the chances of accurate evaluation.

Along the same lines, **bi-capsule** or **poly-capsule** systems can be used to

- examine different parts of the body simultaneously, improving diagnosis in terms of inspection time, capsule active locomotion, visualization and communication performance, etc.

- realize complicated kinematics for real surgical tasks, often requiring a bi-manual tele-operated approach (**Law of Harmonization of Rhythms** will also play a role here).

Figure 11. Increasing number of systems

6.2.2 Line of increasing diversity of systems

The initial capsule type endoscopy system was essentially a **homogenous** system in terms of overall endoscopic function, playing the role of visualization, although at a sub-system level, one could argue that the capsule endoscope is a **heterogeneous** system. In either case, the amount of heterogeneity can only increase from hereon in.

An increase in sub-systems with **shifted properties** goes hand in hand with the programmable, controllable nature of systems discussed above. For example,

- Illumination systems that can adjust illumination intensity
- Imaging systems that adjust brightness, hue, saturation, contrast etc.
- Capsules customized for different regions of the body

Adding diagnostic and therapeutic capabilities is definitely an immediate next step towards **heterogeneity**. We can already see evidence of the same in the form of inventions focused on introducing steerable diagnostic and/or therapeutic devices such as a biopsy device, a drug release device, or a diagnostic or treatment device. For example,

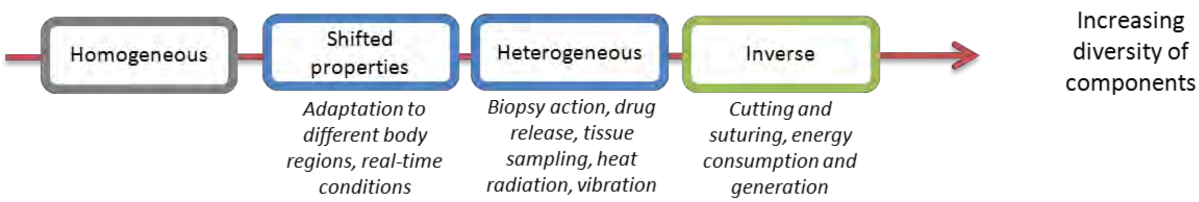
- Biopsy action - a remote magnetic signals or wireless RF signals could be utilized for biopsy action, or drug release from the capsule compartment, at specific time (CN101011234 (A), United States Patent no. 6,776,165)
- Collecting tissue samples - a bioMEMS device was utilized for collecting tissue sample for biopsy
- a local ultrasonic wave source and/or detector for localized acoustic diagnosis or treatment (e.g., to damage or disrupt unwanted cell structure)
- a localized x-ray source and/or detector
- a source of intense heat radiation to disrupt or damage tumor growth
- a mechanical vibration source and/or detector to stimulate or slow down cell (United States Patent no. 6,776,165)

- A surgical clip introduced into the wireless capsule system which can be released wirelessly to a target surgical site ((EP 2163206 (A1)) to prevent hemorrhaging, treating of lesion, and marking of suspected tissue area

In the future, sub systems can perform **inverse** functions as well. For example,

- a subsystem in the capsule that is able to do cutting as well as suturing or joining function
- devices that can consume as well as store and generate energy (more on this in the lines of shortening energy flow paths discussed later)
- imaging and illumination sub-systems that can increase brightness as well as increase contrast

Figure 12. Increasing diversity of systems



6.3 Law of Shortening of Energy Flow Path

6.3.1 Increasing controllability of Energy sources

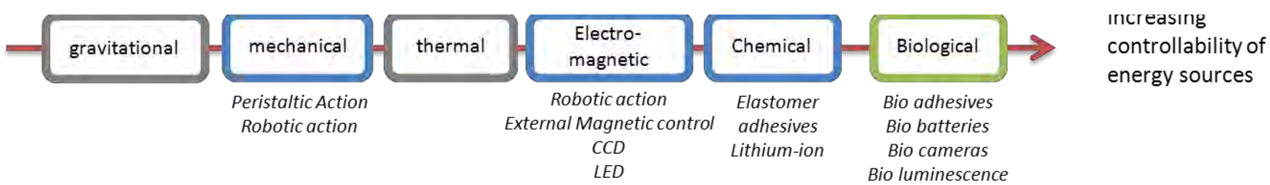
We already have capsule endoscopes that can be controlled externally via **magnetic** means. For example, patent KR20050010590 (A) proposes the guidance of the capsule (and the camera) by introducing paramagnetic material between the camera and the battery and an externally placed magnetic force applying device. **Electromagnetic** communication and control mechanisms suitable for application within the human body such as telemetry are also being explored. This introduces information processing capability and can open up the avenues of precision positioning and control through digital means.

Proposed micro-robotic capsules incorporate **electro-mechanical** means for locomotion, gripping and therapeutic functions. Patent EP 2163206 (A1) describes an invention to provide wireless capsular therapeutic treatment ability with lower energy consuming treatment mechanisms using collapsible stopper mechanisms in the form of fluid inflatable bodies and smart memory alloys. The use of smart materials such as shape memory alloys is along the ***Law of increasing dynamism - the line of increasing use of smart materials***. We also have capsules that incorporate **biomechanical** adhesion mechanisms such as micro-patterned and micro-fibrillar adhesives for more efficient locomotion.

Moving further along the line to **chemical** and **biological** energy sources and fields is an eminent possibility, with the recent advances in biotechnology. This movement is also predicted by the ***Line of Reduced number of Energy Transformation Stages*** according to which the system will move towards **direct application of energy to the working means**.

In this case, since the working means is of biological nature (some portion of the human body to be visualized, diagnosed and treated), it is likely that the energy source, the engine, the transmission and the control unit of each sub-system will move closer to the working unit by employing biotechnological methods.

Figure 13. Increasing controllability of energy sources



- Biological batteries based on enzyme –substrate reaction can be used to generate electricity from sugar using sugar digesting enzymes as the catalyst.
- Bio-bulbs based on the light emitting mechanism of bioluminescent organisms (oxidizable organic molecule luciferin and the enzyme luciferase) can be used for precision illumination
- It is also not entirely inconceivable that we may have bio-cameras (like our eye) introduced into the capsule at some point of time in the future.

6.4 Law of Transition to the Micro-Level

Given the history of endoscope evolution and current interest in nano-technology, it is extremely likely that further transition to the nano-level will happen. A paradigm shift in endoscopy functions and output can be expected at that stage, potentially the beginning of a new cycle of the evolution spiral.

Just to trigger the enthusiasm of science fiction enthusiasts, we may actually have, in the distant future, endoscopic syrup, constituted of nano and bio particles, with a remarkable convolution of examination, drug delivery, diagnosis and therapeutic functions! No more separate endoscopes, the medicine itself will function as an endoscope!

6.5 Other Laws of System Evolution

The Law of Completeness and the Law of Harmonization of Rhythms have been discussed above at relevant points, where the movement along these laws where convergent with movement along other laws such as the Law of Shortening of Energy Flow Path and the Law of Transition to Higher Level System. The Law of Increasing Controllability required a deeper analysis of Su-Fields beyond the scope of this paper.

The Law of Increasing Degree of Ideality has not been explicitly discussed given the fact that it is a macro law underpinning all other laws. The Law of Non-uniform Evolution of Sub-systems has also not been explicitly discussed, although evidence of the same appears throughout the paper in terms of the convergence and divergence of the technological sub-systems that are a part of the endoscopic system.

7 Conclusion

Endoscopy has witnessed tremendous waves of evolution over the years, with a fascinating journey from rigid to flexible endoscopes culminating in the latest capsule endoscope technology. Analyzing this evolution using the TRIZ laws and lines of evolution offers unique insights into the mechanics of this evolution. While it was fairly obvious that the primary evolution line was the increasing flexibility of physical structures, other laws such as the transition to micro-level were creating a super system impact, influencing multiple technologies such as imaging, illumination and communication. These developments were in turn, influencing the general pace and direction of endoscope evolution and creating new branches and leaves on the endoscope evolution tree. Interestingly, some branches such as tubeless endoscopy, were actually created early on, but had to remain muted for a while, waiting for other technologies to develop, before flourishing in full flow. Evolution therefore, even along the laws and lines of evolution, is not necessarily a seamless sequential progression. There are stops, starts and jumps based on how other evolution trees (of different technologies) and other branches within the same tree are developing.

Capsule endoscopy appears to be at the inception stage of its S-curve. Exciting developments can be anticipated along the law of increasing dynamism (with increasing structural and functional flexibility), the law of transition to higher level systems (increasing number and diversity of systems and some convolution), the law of shortening of energy flow path (especially on the proliferation of easier to control energy forms). Capsule endoscopes are playing an increasingly active role in examination, diagnosis and therapy for all traversable parts of the human body. The law of transition to micro-level continues to wield a super-system influence and might trigger a new S-curve in endoscopy in the not too distant future.

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