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Abstract

This deliverable provides a high-level overview of some of the key literature in the field of flexible robotic drive technology. A search term matrix was generated, search queries were programmatically generated from the matrix of search terms and the scopus database was searched for literature from the last ten years. 2038 results were found, and manually reduced to 96 relevant works via a set of inclusion criteria. Results were categorised by application and technology and discussed.

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1. Introduction

In recent years, minimally invasive surgery has raised the bar of what patients have come to expect from surgery - smaller scars, less pain, low complication rates, short hospital stays, minimal impact on the patient's life. These changes have been made possible by a slew of advances in surgical instruments that allow surgeons to see and work inside the human body without making large incisions - in other words, endoscopy. While rigid endoscopy, as part of laparoscopic surgery, has seen rapid improvement and growth, flexible endoscopes have seen a slow pivot from purely diagnostic devices to become more interventional platforms. Since then, the field of natural orifice transluminal endoscopic surgery (NOTES) has emerged. Dallemagne et al. [1] performed key work in transgastric cholecystectomy, heralding a paradigm shift from conventional laparoscopic to effectively scarless surgery.

Flexible endoscopic surgery, however, requires flexible instruments. While attempts such as the ANUBIS system [2] have been made to create a flexible surgical suite, the field is still far from widespread. It can therefore be said that there remains a need for an improvement in the underlying actuation technology of flexible medical robotics with a view to opening the technology up to wider adoption through lower cost, improved precision, usability and reduced OR footprint.

2. Method

To carry out this high-level state of the art survey, the scopus database was used. Search queries were programmatically generated from the search term matrix and query results were automatically retrieved and checked for duplicates via the scopus API. The list of references was saved as a .csv file and manually evaluated according to the inclusion criteria. All items that did not meet the inclusion criteria were excluded. Finally, all relevant material was sorted by medical application and principle of operation and enumerated here.

1. Search terms

The search terms used in this survey were chosen by generalising the term ”soft robotic endoscopic device”. Simply searching for this term alone would lead to much missed information as authors will use different semantics to describe similar ideas, all of which may be relevant to this survey. For example, this document could arguably be called a *literature review* rather than a *state of the art survey*. Regardless, to someone looking for information on soft robotic drive technology, either term may lead to a useful document.

Therefore, in lieu of searching for every possible phrasing, a limited search term matrix was created that the authors believe covers the majority of the relevant literature. In this way, search terms are combined with the logical operators *AND* and *OR* that a very large search space can be covered in great detail.

The following search term matrix was generated:

Soft			Robotic			Intervention type			Device	
soft		AND	autonomous		AND	endoscop*		AND	needle	
compliant	OR		robot*	OR		laparoscop*			*scope	
continu*			assist*			colonoscop*			catheter	OR
flex*			automat*			ureteroscop*	OR		grasp*	
						endovascular*			dissect*	
						percutaneous*				

Table 2.1: Search term matrix

For example, a search query would take the format of *”soft AND robot* AND endovascular* AND catheter”*. This matrix, once all possible combinations have been exhausted, yields some 480 search queries. As it would be impractical to manually enter each one of these queries, download the list of references for each search, add it to the overall list and remove duplicates, this was done using a Python script leveraging the pybliometrics library [3].

Needless to say, some combinations of search terms are less useful than others. Fortunately this is of little concern for several reasons: Firstly, additional queries do not compromise the usefulness of already-executed or planned queries; Secondly, duplicate results are automatically discarded by the python script; Thirdly, each individual search takes very little time to complete, down to one or two seconds if no results are found. Given that the entire series of nearly 500 search queries took about half an hour to complete, even several dozen dud queries are easily ignored. Nevertheless the search was limited to the title, abstract, and keyword fields to keep the program execution time reasonable.

Given this abundance of searching power, the original search term matrix was expanded a little with a view to potentially uncovering obscure-yet-related results. For example, the matrix included *percutaneous* and *laparoscop** as terms, even though results focusing exclusively on these applications would be disallowed by the inclusion criteria (see Section 2).

2. Inclusion Criteria

As the application of soft robotics in medical technology is still comparatively new, the search was limited to literature published in the last ten years. Furthermore, to keep the search relevant to the ATLAS project, results were only included if the authors expressly identified any one of the following as the field of application:

1. Colonoscopy
2. Gastroscopy
3. Endoscopy (in general)
4. Ureteroscopy
5. Transgastric or transanal Natural-Orifice Transluminal Endoscopic Surgery (NOTES)
6. Intravascular procedures

Non-medical results were excluded.

3. Results

The python script returned a detailed comma separated value (CSV) file of some 2038 references. This file was imported into Microsoft Excel and reformatted for legibility, following which the title of each reference was evaluated and either shortlisted or excluded based on the above-listed inclusion criteria. References where the inclusion status was not immediately apparent were included in the shortlist so as not to accidentally disregard potentially relevant material. This process yielded a shortlist of 268 references. The full-text of each entry was located using a combination of EndNote's *find full-text* functionality as well as manually using sources such as the IEEEXplore database.

Of the shortlisted 268, 25 titles were excluded because their full-text files proved too difficult to locate, 147 failed the inclusion criteria upon closer evaluation, leaving 96 titles (a reduction of 95%). The full table of results can be found in Appendix B.

Apart from the original way of sorting publications by medical application, another method presented itself as the material was evaluated. Eight loose categories of drive technology were identified:

- Concentric tube robots
- Electromechanical actuation (translation and rotation) of an otherwise unsteerable pre-formed catheter
- Hydraulic actuation
- Magnetic actuation
- Pneumatic actuation
- Smart Material (shape memory)
- Tendon actuation
- The use of reaction forces on the lumen wall for propulsion

Table 3.1 shows the relationship of technologies and applications. It can be seen that tendon based robots are by far the most common, both overall and in every category other than gastroscopy and colonoscopy.

Table 3.1: A breakdown of the reviewed material by medical application and applied technology. To view individual the individual works in each category, please see Appendix B, Table B.1.

Application:	Ureteroscopy	Endovascular	Gastroscopy	Non-specific	NOTES	Colonoscopy	Totals
No. of Publications:	5	10	11	19	23	28	96
			By applied technology:				
Concentric:				1		1	2
Electromechanical:		1					1
Hydraulic:			1	2	1		4
Magnetic:		1	3	2		5	11
Pneumatic:			4	5	4	3	16
Smart material:				1			1
Tendon-driven:	4	4	3	6	16	8	41
Tissue Reaction:				1		8	9
Review Paper:	1	4		1	2	3	11

Concentric robots featured only in colonoscopy as well as one non-specific design; Ponten et al. [4] evaluated the use of concentric-robot ”arms” as a way of controlling flexible colonoscopic instruments for intraluminal surgery (endoscopic submucosal dissection (ESD)). Wu et al. [5] built a type of steerable micro-endoscope.

Electromechanical actuation systems have a very niche application in endovascular surgery, applied in this case by He et al. [6] in 2018 to robotise a preformed endovascular catheter with variable stiffness.

Berg et al. [7] explored the use of hydraulically-steerable dextrous manipulators for transgastric NOTES surgery. Stopforth et al. [8], [9] designed a low-cost hydraulic system with the express goal of improving access to general endoscopy in South Africa.

The final entry in the hydraulic category, Yin et al. [10] published a very creative approach to endoscope design. Their concept consists of a system of low glass-transition temperature polymer tubes braided around one another. These tubes feed water to the distal tip of the endoscope where it exits the endoscope via a set of nozzles. The force reaction of the water jets pushes the endoscope in the desired direction. The water used for actuation is held between 35 and 45°C, keeping the tubing soft and flexible. To lock the shaft, the outer sheath of the endoscope is flooded with cooling water, dropping the internal temperature of the endoscope and the braided tubing to about 5°C. This pushes the plastic tubing below its glass transition temperature and causes the shaft to become significantly more rigid, thus creating an extremely simple steerable gastroscope with variable stiffness.

Magnetic actuation usually consists of an array of electro- or- electropermanent magnets located outside of the body, with a steerable instrument containing a permanent magnet inside the body. The interaction of the magnetic fields exerts a force on the device inside the body, with no (or a very thin and flexible) connection to the outside. Do [11], Son [12], and Yim [13] explored applications of magnetic gastroscopy, with Son proposing a magnetically-steered capsule endoscope capable of performing fine-needle aspiration (FNA) biopsy. Jeon et al. [14] automated the insertion and rotation of an endovascular catheter using an electromechanical master-slave system with a magnetically-controlled distal tip. Colonoscopy appears to be the most common application of magnetically-actuated systems, with 5 individual works exploring variants of capsule endoscopy.

Pneumatic systems are quite evenly distributed between gastroscopy, colonoscopy, NOTES and non-specific endoscopy. Garbin et al. [15] for example explored low-cost gastroscopy using an endoscope actuated with a system of three parallel bellows. Visualisation was achieved via Wi-Fi based image transmission to a smartphone. Yanmin et al. [16] on the other hand developed a system for the automated insertion and control of a conventional endoscope.

A single work explored shape-memory alloy (SMA) systems - Hadi et al.[17] built a continuum element actuated by the contraction of SMA springs.

Tendon-based control outnumbered all other actuation systems by far, making up some 43% of all the surveyed literature. Work in the last ten years largely focused on NOTES, for example manually-actuated systems such as the ANUBIScope [2] or the master-slave STRAS system [18] presented by De Donno et al in 2013.

A more unusual approach focused almost entirely on colonoscopy is the family of tissue-reaction drives. These are a loosely-defined group of capsule endoscope-like systems using either tank tracks [19][20][21][22], paddles[23][24][25], or worm-like locomotion [26][20].

4. Discussion

The spread of the uncovered literature across applications and technologies paints an image of the advantages and disadvantages of each technical approach to medical robotics. Robots deriving their locomotion from tissue reaction forces, for example, require a large amount of space for recirculating tracks or paddles. The human colon provides the largest lumen diameter when compared to the oesophagus or the vascular system. Between the limiting factors of the technology and the range of available applications it is only logical that the designers would choose colonoscopy as the application.

A similar trend can be observed in NOTES - tendon-based mechanisms are the most mature technology available to build intraluminal robotics, meaning researchers tasked with building such devices will choose this technology because it gives them the shortest turnaround time to a working prototype and offers very high chances of success.

Shape-memory technology remains rare - this is somewhat unsurprising given the fact that Hadi et al [17] reported a deflection of approx. 70° takes on the order of 50 seconds. Note that larger bandwidths up to 2Hz or even higher can be achieved if e.g. sufficient cooling is foreseen, but in general as master-slave control is the most common method of controlling surgical robots, actuation on a faster timescale would be generally required.

One particular work stands out from the magnetic actuation group: Tappe et al. [27] proposed a system with a fully active shaft that requires no bulky external steering magnets. Instead, this system relies on a multitude of smaller magnetic actuators. Each actuator possesses only a small amount of travel, being able to pivot only a few degrees; the sum of many of these units permits the shaft as a whole to bend through large angular displacements. Sadly, this system is quite bulky (the authors hoped for a design diameter of less than 16mm) and produces very large bend radii. Nevertheless, use of many discretely actuated elements to form one long continuum manipulator may be worth exploring.

Variable stiffness systems based on the glass transition of polymers appear to be a promising area of research. Le et al [28] [29] designed a variable-stiffness tube (VST) that uses resistive heating to bring a Polyethylene Terephthalate (PET) tube above its glass transition temperature (67°C) when low stiffness is required. Cooling in ambient air for the described element requires a mere 20 seconds. While this is a problem for actuating elements, it can be argued that a user will not be as acutely aware of the stiffness of a flexible system as of its pose, potentially reducing the perception of input lag. Yin et al's [10] water-jet actuated endoscope uses a similar mechanism of heating and cooling, but circumvents cooling time by using chilled water to cool the plastic immediately, as well as using a polymer with a lower glass transition. A combination of both approaches may be worth investigating in a conventional tendon-actuated system, thereby combining actuation speed with rapidly-switchable stiffness.

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A. Python code

Listing A.1: The script used to quickly return a duplicate-free list of references from scopus

```
from pybliometrics.scopus import ScopusSearch
import pandas as pd
import time

#Define search term lists recursively

softBody = ["soft", "compliant", "coninu*","flex*"]

robotic = ["autonomous", "robot*", "assist*", "automat*"]

application = ["endoscop*", "laparoscop*", "colonoscop*", "ureteroscop*", "endovascular", "percutaneous*"]

device = ["Needle", "*scope", "catheter", "grasp*","dissect*"]

additionalParams = " PUBYEAR > 2009"

#empties to hold outputs
output = []
searchTerm = ""

#Begin generating search queries from above lists

#for every item in softBody
for i in enumerate(softBody):
      #add the current item to the searchTerm string
      searchTerm += i[1]
      #add a space and AND
      searchTerm += " AND "
      #then take the next term from robotic
      for j in enumerate(robotic):
            #add the term and AND to the searchTerm string
            searchTerm += j[1]
            searchTerm += " AND "

            for k in enumerate(application):
                  #add the next term from application as well as an AND
                  searchTerm += k[1]
                  searchTerm += " AND "

                  for l in enumerate(device):
                        #add the final term
                        searchTerm += l[1]
                        output.append(searchTerm)
                        #remove the last added term to prepare for the next permutation
                        length = len(l[1])
                        searchTerm = searchTerm[0:-length]
                  #remove the last added term to prepare for the next
```

```
                        permutation
                    length = (len(k[1])+5)
                    searchTerm = searchTerm[0:-length]
                #remove the last added term to prepare for the next permutation
                length = (len(j[1])+5)
                searchTerm = searchTerm[0:-length]
        #remove the last added term to prepare for the next permutation
        length = (len(j[1])+5)
        searchTerm = searchTerm[0:-length]

#create an empty python dataframe to hold the search results

resultRepo = pd.DataFrame(columns = ['eid', 'doi', 'pii', 'pubmed_id', 'title', 'subtype', 'creator', 'afid',
      'affilname', 'affiliation_city', 'affiliation_country', 'author_count',
      'author_names', 'author_ids', 'author_afids', 'coverDate',
      'coverDisplayDate', 'publicationName', 'issn', 'source_id', 'eIssn',
      'aggregationType', 'volume', 'issueIdentifier', 'article_number',
      'pageRange', 'description', 'authkeywords', 'citedby_count',
      'openaccess', 'fund_acr', 'fund_no', 'fund_sponsor'])

#inform the user how many search queries the program will fire off

print("Generated {:d} search terms.\n".format(len(output)))

#for each generated search query

for i in enumerate(output):
        #limit the search to a title, abstract and keyword search
        query = "TITLE-ABS-KEY(" + i[1]+ ")" + additionalParams
        #calculate the progress percentage
        percentage = (i[0]/len(output))*100
        #inform the user of what term is being searched and what the current progress is
        print("Searching term {:d} of {:d} ({:.2f}%): \"{}\"".format(i[0], len(output), percentage, query))

        #create a scopus search with the query we generated above
        s = ScopusSearch(query,view = 'STANDARD')
        #reformat the search results as a pandas dataframe
        searchResults = pd.DataFrame(s.results)
        #append the results from this particular query to the list of results
        resultRepo = resultRepo.append(searchResults)
        #remove any duplicates
        resultRepo.drop_duplicates(keep="first",inplace=True)
        numResults = len(resultRepo.index)

        #tell the user how many results were found and how many unique results have been found
        print("{:d} results found for this term.\n{:d} unique results so far.\n".format(s.get_results_size(),numResults))

#print the output to give the user a quick way to sanity check the output
print(resultRepo)
#store the list of references as a csv file
export_csv = resultRepo.to_csv (r'C:\\Users\\Fabian\\Documents\\LitResults.csv',
```

```
 index = None, header=True) #Don't forget to add '.csv' at the end of the
path
```

B. Summary of reviewed literature

Table B.1: Complete list of included publications

Title	1st Author	Publication	Year	Technology	Application
Analysis of a concentric-tube robot design and feasibility for endoscopic deployment	Ponten [4]	Conference Proceedings	2017	Concentric	Colonoscopy
An innovative robotic platform for magnetically-driven painless colonoscopy	Bianchi [30]	Annals of Translational Medicine	2017	Magnetic	Colonoscopy
Explicit Model Predictive Control of a Magnetic Flexible Endoscope	Scaglioni [31]	IEEE Robotics and Automation Letters	2019	Magnetic	Colonoscopy
Autonomous Retroflexion of a Magnetic Flexible Endoscope	Slawinski [32]	IEEE Robotics and Automation Letters	2017	Magnetic	Colonoscopy
Autonomously Controlled Magnetic Flexible Endoscope for Colon Exploration	Slawinski [33]	Gastroenterology	2018	Magnetic	Colonoscopy
Magnetic air capsule robotic system: proof of concept of a novel approach for painless colonoscopy	Valdastri [34]	Surgical Endoscopy	2012	Magnetic	Colonoscopy
Development of autonomous microrobotics in endoscopy	Cheng [35]	Journal of Medical Engineering & Technology	2011	N/A	Colonoscopy
Robotics for Advanced Therapeutic Colonoscopy	Wong [36]	Clinical Endoscopy	2018	N/A	Colonoscopy
Emerging next?generation robotic colonoscopy systems towards painless colonoscopy	Yeung [37]	Journal of Digestive Diseases	2019	N/A	Colonoscopy
Design and preliminary evaluation of a self-steering, pneumatically driven colonoscopy robot	Dehghani [38]	Journal of Medical Engineering & Technology	2017	Pneumatic	Colonoscopy
Fabrication and basic experiments of pneumatic multi-chamber rubber tube actuator for assisting colonoscope insertion	Wakimoto [39]	Conference Proceedings	2010	Pneumatic	Colonoscopy
Development of a peristaltic crawling robot attached to a large intestine endoscope using bellows - type artificial rubber muscles	Yanagida [40]	Conference Proceedings	2012	Pneumatic	Colonoscopy
A Novel Robotic Meshworm With Segment-Bending Anchoring for Colonoscopy	Bernth [41]	IEEE Robotics and Automation Letters	2017	Tendon-driven	Colonoscopy

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Title	1st Author	Publication	Year	Technology	Application
Development of a novel endoscopic manipulation system: the Endoscopic Operation Robot ver.3	Kume [42]	Endoscopy	2015	Tendon-driven	Colonoscopy
Endoluminal surgical triangulation 2.0: A new flexible surgical robot. Preliminary pre-clinical results with colonic submucosal dissection	Legner [43]	The International Journal of Medical Robotics and Computer Assisted Surgery	2017	Tendon-driven	Colonoscopy
Robotic-assisted flexible colonoscopy: preliminary safety and efficiency in humans	Rozeboom [44]	Gastrointestinal Endoscopy	2016	Tendon-driven	Colonoscopy
Feasibility of joystick guided colonoscopy	Rozeboom [45]	Journal of Robotic Surgery	2015	Tendon-driven	Colonoscopy
Design and evaluation of robotic steering of a flexible endoscope	Ruiter [46]	Conference Proceedings	2012	Tendon-driven	Colonoscopy
Robotic control of a traditional flexible endoscope for therapy	Ruiter [47]	Journal of Robotic Surgery	2013	Tendon-driven	Colonoscopy
Development of a Robotic Colonoscopic Manipulation System, Using Haptic Feedback Algorithm	Woo [48]	Yonsei Medical Journal	2017	Tendon-driven	Colonoscopy
A self-propelled robotic colonoscope using elastic caterpillars	Dowon [49]	Conference Proceedings	2013	Tissue Reaction	Colonoscopy
A paddling mechaism based robotic colonoscope harnessing flexible shaft	Joe [23]	Conference Proceedings	2015	Tissue Reaction	Colonoscopy
Input signal effects on the locomotion of a robotic colonoscope activated by a flexible shaft	Joe [24]	International Journal of Precision Engineering and Manufacturing	2017	Tissue Reaction	Colonoscopy
The flexible caterpillar based robotic colonoscope actuated by an external motor through a flexible shaft	Kim [20]	Journal of Mechanical Science and Technology	2014	Tissue Reaction	Colonoscopy
An elastic caterpillar-based self-propelled robotic colonoscope with high safety and mobility	Lee [21]	Mechatronics	2016	Tissue Reaction	Colonoscopy
A reel mechanism-based robotic colonoscope with high safety and maneuverability	Lee [50]	Surgical Endoscopy	2019	Tissue Reaction	Colonoscopy
Full-driving soft robotic colonoscope in compliant colon tissue	Wang [26]	Journal of Medical Engineering & Technology	2017	Tissue Reaction	Colonoscopy

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Title	1st Author	Publication	Year	Technology	Application
A quasi-static model of wheel-tissue interaction for surgical robotics	Wang [22]	Medical Engineering & Physics	2013	Tissue Reaction	Colonoscopy
A linear stepping endovascular intervention robot with variable stiffness and force sensing	He [6]	International Journal of Computer Assisted Radiology and Surgery	2018	Electromechanical	Endovascular
A Magnetically Controlled Soft Microrobot Steering a Guidewire in a Three-Dimensional Phantom Vascular Network	Jeon [14]	Soft Robotics	2019	Magnetic	Endovascular
Flexible Instruments for Endovascular Interventions: Improved Magnetic Steering, Actuation, and Image-Guided Surgical Instruments	Heunis [51]	IEEE Robotics & Automation Magazine	2018	N/A	Endovascular
Flexible robotic catheters in the visceral segment of the aorta: advantages and limitations	Li [52]	The Journal of Cardiovascular Surgery	2018	N/A	Endovascular
Trends in robot assisted endovascular catheterization technology: A review	Rijanto [53]	Conference Proceedings	2017	N/A	Endovascular
Flexible robotics in pelvic disease: does the catheter increase applicability of embolic therapy?	Rueda [54]	The Journal of Cardiovascular Surgery	2018	N/A	Endovascular
Tendon-Driven Continuum Robot for Endoscopic Surgery: Preclinical Development and Validation of a Tension Propagation Model	Kato [55]	IEEE/ASME Transactions on Mechatronics	2015	Tendon-driven	Endovascular
Electromagnetic tracking of flexible robotic catheters enables ?assisted navigation? and brings automation to endovascular navigation in an in vitro study	Schwein [56]	Journal of Vascular Surgery	2018	Tendon-driven	Endovascular
Flexible robotics with electromagnetic tracking improves safety and efficiency during in vitro endovascular navigation	Schwein [57]	Journal of Vascular Surgery	2017	Tendon-driven	Endovascular
Experimental validation of robot-assisted cardiovascular catheterization: model-based versus model-free control	Wang [58]	International Journal of Computer Assisted Radiology and Surgery	2018	Tendon-driven	Endovascular

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Title	1st Author	Publication	Year	Technology	Application
Water-jet outer sheath with braided shape memory polymer tubes for upper gastrointestinal tract screening	Yin [10]	The International Journal of Medical Robotics and Computer Assisted Surgery	2018	Hydraulic	Gastroscopy
A magnetic soft endoscopic capsule for non-surgical overweight and obese treatments	Do [11]	Conference Proceedings	2016	Magnetic	Gastroscopy
Magnetically actuated soft capsule endoscope for fine-needle aspiration biopsy	Son [12]	Conference Proceedings	2017	Magnetic	Gastroscopy
Design and Rolling Locomotion of a Magnetically Actuated Soft Capsule Endoscope	Yim [13]	IEEE Transactions on Robotics	2012	Magnetic	Gastroscopy
A disposable continuum endoscope using piston-driven parallel bellow actuator	Garbin [59]	Conference Proceedings	2018	Pneumatic	Gastroscopy
Dual-Continuum Design Approach for Intuitive and Low-Cost Upper Gastrointestinal Endoscopy	Garbin [15]	IEEE Transactions on Biomedical Engineering	2019	Pneumatic	Gastroscopy
Design and control of a novel gastroscope intervention mechanism with circumferentially pneumatic-driven clamping function: A novel GIM with circumferentially pneumatic-driven clamping function	Li [60]	The International Journal of Medical Robotics and Computer Assisted Surgery	2017	Pneumatic	Gastroscopy
A novel gastroscope intervention mechanism with circumferentially pneumatic-driven clamping function	Yanmin [16]	Conference Proceedings	2015	Pneumatic	Gastroscopy
A new robotic-assisted flexible endoscope with single-hand control: endoscopic submucosal dissection in the ex vivo porcine stomach	Iwasa [61]	Surgical Endoscopy	2018	Tendon-driven	Gastroscopy
Automate surgical tasks for a flexible Serpentine Manipulator via learning actuation space trajectory from demonstration	Xu [62]	Conference Proceedings	2016	Tendon-driven	Gastroscopy
Design of a steering mechanism for a Tethered Capsule Endoscope	Ye [63]	Conference Proceedings	2015	Tendon-driven	Gastroscopy
Towards hybrid control of a flexible curvilinear surgical robot with visual/haptic guidance	Wu [5]	Conference Proceedings	2016	Concentric	non-specific

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Title	1st Author	Publication	Year	Technology	Application
Low cost robotic endoscope design considerations	Stopforth [8]	Conference Proceedings	2016	Hydraulic	non-specific
Low cost soft endoscope robotic probe	Stopforth [9]	Conference Proceedings	2017	Hydraulic	non-specific
Towards a follow-the-leader control for a binary actuated hyper-redundant manipulator	Tappe [27]	Conference Proceedings	2015	Magnetic	non-specific
A compensation strategy for accurate orientation of a tethered robotic capsule endoscope	Zhang [64]	Conference Proceedings	2017	Magnetic	non-specific
Application of robotics in gastrointestinal endoscopy: A review	Yeung [65]	World Journal of Gastroenterology	2016	N/A	non-specific
A natural orifice soft robot with novel driven method for minimally invasive surgery (MIS)	Hao [66]	Conference Proceedings	2017	Pneumatic	non-specific
Soft-Robotic Endoscope Tip Design	Nuriyev [67]	Conference Proceedings	2017	Pneumatic	non-specific
Design of wormlike automated robotic endoscope: dynamic interaction between endoscopic balloon and surrounding tissues	Poon [68]	Surgical Endoscopy	2016	Pneumatic	non-specific
Pneumatic flexible hollow shaft actuator with high speed and long stroke motion	Wakana [69]	Conference Proceedings	2013	Pneumatic	non-specific
A micro soft robot using inner air transferring for colonoscopy	Wang [70]	Conference Proceedings	2013	Pneumatic	non-specific
Developing a novel continuum module actuated by shape memory alloys	Hadi [17]	Sensors and Actuators A: Physical	2016	Shape-Memory Alloy	non-specific
Design and Development of In Vivo Robot for Biopsy	Garg [71]	Mechanics Based Design of Structures and Machines	2014	Tendon-driven	non-specific
Design and Fabrication of a 3-D Printed Metallic Flexible Joint for Snake-Like Surgical Robot	Hu [72]	IEEE Robotics and Automation Letters	2019	Tendon-driven	non-specific
A Flexible Surgical Robotic System for Removal of Early-Stage Gastrointestinal Cancers by Endoscopic Submucosal Dissection	Lau [73]	IEEE Transactions on Industrial Informatics	2016	Tendon-driven	non-specific
Evaluation of a novel flexible snake robot for endoluminal surgery	Patel [74]	Surgical Endoscopy	2015	Tendon-driven	non-specific

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Title	1st Author	Publication	Year	Technology	Application
ESD CYCLOPS: A New Robotic Surgical System for GI Surgery	Vrielink [75]	Conference Proceedings	2018	Tendon-driven	non-specific
A Novel Telemanipulated Robotic Assistant for Surgical Endoscopy: Preclinical Application to ESD	Zorn [76]	IEEE Transactions on Biomedical Engineering	2018	Tendon-driven	non-specific
Hybrid magnetic mechanism for active locomotion based on inchworm motion	Kim [19]	Smart Materials and Structures	2013	Tissue Reaction	non-specific
Achieving Dexterous Manipulation for Minimally Invasive Surgical Robots Through the Use of Hydraulics	Berg [7]	Conference Proceedings	2012	Hydraulic	NOTES
A review on recent advances in soft surgical robots for endoscopic applications	Gifari [77]	The International Journal of Medical Robotics and Computer Assisted Surgery	2019	N/A	NOTES
Flexible robotic endoscopy: current and original devices	Kume [78]	Computer Assisted Surgery	2016	N/A	NOTES
Evaluation of design aspects of modular pneumatic soft robotic endoscopes	Lenssen [79]	Conference Proceedings	2019	Pneumatic	NOTES
Development of a Multi-level Stiffness Soft Robotic Module with Force Haptic Feedback for Endoscopic Applications*	Naghibi [80]	Conference Proceedings	2019	Pneumatic	NOTES
Soft pop-up mechanisms for micro surgical tools: Design and characterization of compliant millimeter-scale articulated structures	Russo [81]	Conference Proceedings	2016	Pneumatic	NOTES
Variable stiffness outer sheath with ?Dragon skin? structure and negative pneumatic shape-locking mechanism	Zuo [82]	International Journal of Computer Assisted Radiology and Surgery	2014	Pneumatic	NOTES
Improvements in the control of a flexible endoscopic system	Bardou [83]	Conference Proceedings	2012	Tendon-driven	NOTES
A Novel Robotic Suturing System for Flexible Endoscopic Surgery	Cao [84]	Conference Proceedings	2019	Tendon-driven	NOTES

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Title	1st Author	Publication	Year	Technology	Application
Feasibility of transanal total mesorectal excision (taTME) using the Medrobotics Flex? System	Carmichael [85]	Surgical Endoscopy	2019	Tendon-driven	NOTES
The ANUBIS? project	Dallemagne [2]	Minimally Invasive Therapy & Allied Technologies	2010	Tendon-driven	NOTES
Master/slave control of flexible instruments for minimally invasive surgery	De Donno [18]	Conference Proceedings	2013	Tendon-driven	NOTES
Introducing STRAS: A new flexible robotic system for minimally invasive surgery	De Donno [86]	Conference Proceedings	2013	Tendon-driven	NOTES
Designing, Prototyping, and Testing a Flexible Suturing Robot for Transanal Endoscopic Microsurgery	Hu [87]	IEEE Robotics and Automation Letters	2019	Tendon-driven	NOTES
Design and modelling of a variable stiffness manipulator for surgical robots	Le [29]	Mechatronics	2018	Tendon-driven	NOTES
Towards active variable stiffness manipulators for surgical robots	Le [28]	Conference Proceedings	2017	Tendon-driven	NOTES
Robotic endoscopy system (easyEndo) with a robotic arm mountable on a conventional endoscope	Lee [25]	Conference Proceedings	2019	Tendon-driven	NOTES
Flexible endoscopic robot	Lomanto [88]	Minimally Invasive Therapy & Allied Technologies	2015	Tendon-driven	NOTES
CYCLOPS: A versatile robotic tool for bimanual single-access and natural-orifice endoscopic surgery	Mylonas [89]	Conference Proceedings	2014	Tendon-driven	NOTES
Evaluation of robotically controlled advanced endoscopic instruments: Evaluation of robotically controlled advanced endoscopic instruments	Reilink [90]	The International Journal of Medical Robotics and Computer Assisted Surgery	2013	Tendon-driven	NOTES
Interdisciplinary development of a single-port robot	Roppenecker [91]	Conference Proceedings	2012	Tendon-driven	NOTES
How to Design and Create a Cardan Shaft for a Single Port Robot by Selective Laser Sintering	Roppenecker [92]	Conference Proceedings	2012	Tendon-driven	NOTES

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Title	1st Author	Publication	Year	Technology	Application
Haptic feedback and control of a flexible surgical endoscopic robot	Wang [93]	Computer Methods and Programs in Biomedicine	2013	Tendon-driven	NOTES
Robot-assisted flexible ureteroscopy: an update	Rassweiler [94]	Urolithiasis	2018	N/A	Ureteroscopy
Controlling the Trajectory of a Flexible Ultrathin Endoscope for Fully Automated Bladder Surveillance	Burkhardt [95]	IEEE/ASME Transactions on Mechatronics	2014	Tendon-driven	Ureteroscopy
A New Robot for Flexible Ureteroscopy: Development and Early Clinical Results (IDEAL Stage 1?2b)	Saglam [96]	European Urology	2014	Tendon-driven	Ureteroscopy
Robotically assisted ureteroscopy for kidney exploration	Talari [97]	Conference Proceedings	2017	Tendon-driven	Ureteroscopy
Robotic assistance for manipulating a flexible endoscope	Zhang [98]	Conference Proceedings	2014	Tendon-driven	Ureteroscopy

The ATLAS project

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Horizon 2020