

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**A RESONANT PULLEY ACTUATOR FOR SCANNING
CAPSULE ENDOSCOPY**



M.Sc. THESIS

Engincan TEKİN

Electronics and Communication Engineering

Electronics Engineering Programme

JULY 2023

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Thesis Advisor: Asst. Prof. Onur FERHANOĞLU

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**LAZER TARAMALI KAPSÜL ENDOSKOP CİHAZI İÇİN
REZONANS MAKARA EYLEYİCİ**

YÜKSEK LİSANS TEZİ

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(504201212)**

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Tez Danışmanı: Asst. Prof. Onur FERHANOĞLU

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Engincan Tekin, a M.Sc. student of İTÜ Graduate School student ID 504201212, successfully defended the thesis entitled “A Resonant Pulley Actuator for Scanning Capsule Endoscopy”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Onur FERHANOĞLU**
İstanbul Technical University

Jury Members : **Asst. Prof. Ahmet Can Erten**
İstanbul Technical University

Asst. Prof. Baykal Sarıoğlu
İstanbul Bilgi University

Date of Submission : 29 May 2023

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To my family,



FOREWORD

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ABBREVIATIONS

FDM	: Fused Deposition Modeling
PLA	: Polylactic Acid
TPU	: Thermoplastic Polyurethane
GI	: Gastrointestinal
WCE	: Wireless Capsule Endoscopy
TCE	: Tethered Capsule Endoscopy
FEA	: Finite Element Analysis
USAF	: United States Air Force Target



SYMBOLS

Hz	: Hertz (frequency)
°	: Degree
k_c	: Cantilever spring constant
E_c	: Young's Modulus
k_s	: Nylon string spring constant
C_c	: Capacitance (cantilever)
L_c	: Inductance (cantilever)
R	: Resistance (cantilever)
C_s	: Capacitance (string)
L_r	: Inductance (rotating body)



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A RESONANT PULLEY ACTUATOR FOR SCANNING CAPSULE ENDOSCOPY

SUMMARY

Endoscopy is a medical procedure that involves the use of an endoscope, a flexible tube with a light and a camera attached to it, to visualize and examine the interior of various organs and body cavities. The endoscope is inserted through a natural body opening or a small incision and allows doctors to view the internal structures in real-time. Capsule endoscopy is a minimally invasive diagnostic procedure used to visualize the digestive tract, particularly the small intestine. It involves swallowing a small, pill-sized capsule that contains a tiny camera, light source, and transmitter. As the capsule travels through the digestive system, it captures high-quality images of the intestinal lining. These images are wirelessly transmitted to a data recorder worn on a belt around the patient's waist. We present a compact electromagnetically actuated 3D-printed rotary actuator for use in Scanning Capsule Endoscopy. The actuator comprises two cantilevers connected to a rotating body via nylon strings. External coils and the magnets placed on the cantilevers create an electromagnetic force with which the rotation can be initiated. Opposite coils are driven out-of-phase to enable resonant actuation. An electrical circuit model and finite element simulation results of the fundamental mode frequency are provided for the designed device. The design is manufactured via fused deposition modeling using polylactic acid (PLA) and thermoplastic polyurethane (TPU). Experimental results reveal a 98° total scan angle at 21 Hz resonance for the TPU actuator and a 19.7° total scan angle at 237 Hz resonance for the PLA actuator. Overall, the presented rotary actuator compares favorably over i) micromotor counterparts in terms of form factor (having a diameter of 13 mm and a total height of 7 mm) and ii) MEMS counterparts in terms of total scan angle. Manufacturing cost and duration are yet other benefits of the presented device, owing to 3D printing. With further development, the presented device can serve within a disposable capsule endoscopy unit for clinical use.



LAZER TARAMALI KAPSÜL ENDOSKOP CİHAZI İÇİN REZONANS MAKARA EYLEYİCİ

ÖZET

Endoskopi, tıbbi bir prosedürdür ve endoskop adı verilen bir cihaz aracılığıyla iç organların görsel muayenesini gerçekleştirmeyi hedefler. Endoskop, kamera donanımlı esnek bir tüpten oluşan bir cihazdır. Bu yöntem, sindirim sistemi, solunum sistemi, ürogenital sistem ve eklem boşlukları gibi farklı anatomik bölgelerde teşhis koyma, tedavi uygulama ve cerrahi müdahale için değerli bir araç olarak kullanılmaktadır.

Ancak, endoskopi prosedürleri bazı zorluklarla karşılaşabilir. Birincisi, invaziv niteliğidir. Endoskopun vücut içine yerleştirilmesiyle birlikte hastada rahatsızlık ve bazen hafif ağrı hissi meydana gelebilir. Bu nedenle, hastanın konforunu sağlamak amacıyla genellikle sedasyon veya anestezi uygulanır. İkinci bir zorluk, endoskopun hedeflenen bölgelere erişimi ve doğru pozisyonlandırılmasıyla ilgilidir. Bazı durumlarda, dar geçişler, kıvrımlar veya anatomik engeller nedeniyle endoskopun ilerlemesi güç olabilir. Bu durumlar, prosedür süresini uzatabilir ve bazen başarısızlıkla sonuçlanabilir.

Diğer bir zorluk ise görüntü kalitesidir. Endoskopun ucundaki kamera, iç organların net bir görüntüsünü sağlar; ancak, zaman zaman görüntü kalitesi yetersiz olabilir. Özellikle kan, mukus veya diğer sıvılar gibi engelleyici faktörler varsa, görüntü netliği azalabilir. Bu durum, doğru bir teşhis koymayı veya ayrıntılı bir değerlendirme yapmayı zorlaştırabilir.

Endoskopi, cerrahi müdahalelerin gerçekleştirilebileceği bir alanı da içermektedir, ancak bu durum da belirli zorluklar doğurabilmektedir. Cerrahi endoskopi, minimal invazivlik ilkesine uygun olarak organlara ulaşmayı hedefler; fakat bazı durumlarda, karmaşık cerrahi prosedürler gerektiğinde daha fazla invazivlik gerekmektedir.

Kapsül endoskopi, tıbbi görüntüleme tekniklerinden biridir ve sindirim sistemi gibi iç organların görsel muayenesini yapmayı amaçlar. Bu yöntem, bir kapsül şeklindeki bir cihazın yutulması yoluyla gerçekleştirilir. Kapsül, içerisinde bir kamera, ışık kaynağı ve veri kaydedici bir sistem bulunduran bir endoskopik kapsüldür. Hastanın sindirim sistemi boyunca hareket ederken, kapsül tarafından elde edilen görüntüler kaydedilir ve daha sonra bir bilgisayarda incelenir.

Kapsül endoskopi, özellikle geleneksel endoskopi yöntemlerinin ulaşamadığı veya zor ulaşılan bölgelerin değerlendirilmesi için oldukça değerli bir araçtır. Sindirim sisteminin üst kısımları, ince bağırsaklar ve bazı durumlarda kalın bağırsak gibi alanlar, geleneksel endoskopların sınırlamaları nedeniyle tam olarak görüntülenemeyebilir. Kapsül endoskopi, bu bölgelerde ayrıntılı bir inceleme yapma imkanı sunarak tanısal bilgilerin elde edilmesini sağlar.

Kapsül endoskopinin bir avantajı, minimal invazivlik ve hastanın konforudur. Kapsülün yutulmasıyla birlikte hasta normal günlük aktivitelerine devam edebilir,

çünkü kapsül kendiliğinden ilerler ve dışıyla atılır. Bu, hastalar için endoskopik prosedürlerin geleneksel invazivlik ve rahatsızlık potansiyelini azaltır.

Ancak, kapsül endoskopisinin bazı zorlukları vardır. Birincisi, kapsülün kontrol edilebilirliği sınırlıdır. Hastanın iç organlarında hareket ederken tam olarak yönlendirilemez ve hedeflenen bölgelere ulaşma garantisi yoktur. Ayrıca, kapsül endoskopisinin geleneksel endoskopilere kıyasla daha az görüntü kalitesi sağladığı bilinmektedir. Kapsülün küçük boyutu, kamera lensinin ve ışık kaynağının sınırlı kapasitesine yol açabilir, bu da bazı durumlarda netlik ve ayrıntı eksikliğine neden olabilir.

Lazer taramalı kapsül endoskop cihazı, yenilikçi bir görüntüleme teknolojisi kullanarak iç organların detaylı bir şekilde incelenmesini sağlayan bir tıbbi cihazdır. Bu cihaz, iç organların yüzeylerini tarayan bir lazer ışığı kullanır ve geriye yansıyan veya saçılan ışık sinyallerini algılamak için bir algılama sistemi kullanır.

Cihazda yüksek güçlü bir lazer kaynağı bulunur. Bu lazer kaynağı, iç organların taranması için ışık demetlerinin üretilmesini sağlar. Algılama sistemi ise lazer taraması sonucunda geriye yansıyan veya saçılan ışık sinyallerini algılar. Bu sistemin amacı, ışık sinyallerini analiz etmek ve yüksek çözünürlüklü görüntüler elde etmek için çeşitli filtreleme ve işleme tekniklerini kullanmaktır. Ayrıca, cihazda bir veri kaydedici birim bulunur. Bu birim, iç organların görüntülerini kaydederek depolamak için kullanılır.

Lazerin odaklanması ve hareketi için ise lazer taramalı kapsül endoskop cihazında özel bir mercek sistemi ve motor ekipmanları bulunur. Mercek sistemi, lazer ışığını odaklamak ve iç organların yüzeylerini hassas bir şekilde tarayabilmek için kullanılır. Motor sistemi ise kapsül endoskopun 360 derece tarama yapmasına imkan sağlar.

Lazer taramalı kapsül endoskop cihazı, bu ekipmanlar ve ek olarak lazerin odaklanması ve hareketi için kullanılan mercek ve motor ekipmanları aracılığıyla iç organları ayrıntılı bir şekilde görüntüleyebilme kabiliyetine sahiptir. Bu teknoloji, tıp alanında tanınan amaçlar için önemli bir araçtır ve geleneksel endoskopi yöntemlerinin sınırlamalarını aşma potansiyeline sahiptir.

Elbette, kapsül endoskopinin boyutları, üreticiler için bazı zorluklar doğurabilir. Kapsül endoskopinin küçük boyutlarda olması, alan açısından bir kısıtlama getirir ve bu da tasarım ve üretim sürecinde bazı zorlukları beraberinde getirir.

İlk olarak, kapsül endoskopunun küçük boyutlarda olması, içine sığdırılması gereken tüm ekipmanların sınırlı bir alanda yer almasını gerektirir. Algılama sistemleri, veri kaydedici birim, enerji kaynağı ve iletişim bileşenleri gibi farklı bileşenlerin entegrasyonu, sınırlı alan içinde uyumlu bir şekilde gerçekleştirilmelidir. Bu, üreticilerin tasarım sürecinde optimize edilmiş ve kompakt bileşenler kullanmalarını gerektirir.

Bu tezin konusu olan çalışmanın amacı kapsül endoskopi'deki mikromotorun yerini alacak, kapladığı hacim olarak mikromotordan daha kullanışlı ve güç tüketimi anlamında da rakip olabilecek bir döngüsel eyleyici üretmektir. Bu eyleyicinin üretiminde 3 boyutlu baskı metodu kullanılmıştır.

3 boyutlu baskı (3D baskı), katman katman malzeme biriktirme prensibine dayanan bir üretim teknolojisidir. Bu teknoloji, dijital bir modelin bilgisayar destekli tasarım (CAD) yazılımı kullanılarak oluşturulması ve daha sonra bir 3D yazıcı tarafından gerçek dünya nesnesine dönüştürülmesini sağlar. 3 boyutlu baskı, tasarımcıların

karmaşık geometrili ve özelleştirilmiş nesnelere hızlı bir şekilde üretmelerine olanak tanıyan, endüstride de geniş bir kullanım alanı bulmuştur.

3 boyutlu baskı, çeşitli malzemelerin kullanılmasını sağlar. Plastikler, metal alaşımları, seramikler ve biyolojik materyaller gibi farklı malzeme türleri 3 boyutlu baskı için kullanılabilir. Bu sayede, endüstriler arasında prototipleme, üretim parçalarının üretilmesi, tıbbi implantlar, özelleştirilmiş protezler ve sanatsal eserler gibi birçok uygulama alanı bulunur.

3 boyutlu baskının bazı avantajları vardır. Öncelikle, karmaşık geometrili nesnelere üretilmesini kolaylaştırır ve tasarımcılar için daha fazla özgürlük sağlar. Ayrıca, hızlı prototipleme sürecini hızlandırır ve üretim maliyetlerini azaltır. Bunun yanı sıra, özelleştirilmiş ürünlerin tasarımı ve üretimi için büyük bir potansiyel sunar.

Verilen bilgiler ışığında bu çalışmada; Tarama Kapsülü Endoskopisinde kullanılmak üzere kompakt elektromanyetik olarak hareket ettirilen 3D baskılı bir döner eyleyici sunulmaktadır. Eyleyici, karşılıklı iki dirsekli yapının naylon iplerle dönen bir gövdeye bağlandığı bir yapıya sahiptir. Harici bobinler ve dirsekli yapıya yerleştirilen mıknatıslar, dönme hareketini başlatan elektromanyetik bir kuvvet oluşturur. Ters kutuplu bobinler, rezonanslı hareketi mümkün kılmak için farklı fazlarda sürülür. Tasarlanan cihazın elektrik devre modeli ve temel mod frekansına ilişkin sonlu eleman simülasyonu sonuçları sunulmaktadır. Tasarım, polilaktik asit (PLA) ve termoplastik poliüretan (TPU) kullanılarak birleşik depozisyon modelleme yöntemiyle üretilmektedir. Deneysel sonuçlar, TPU eyleyicisi için 21 Hz rezonans frekansında 98 °'lik toplam tarama açısı ve PLA eyleyicisi için 237 Hz rezonans frekansında 19.7 °'lik toplam tarama açısı elde edildiğini göstermektedir. Genel olarak, sunulan döner eyleyici, i) mikromotor benzerlerine göre form faktörü açısından (13 mm çapında ve 7 mm toplam yükseklikte) ve ii) MEMS benzerlerine göre toplam tarama açısı açısından avantajlıdır. 3D baskının sağladığı üretim maliyeti ve süresi, sunulan cihazın diğer faydaları arasındadır. Daha fazla geliştirme ile sunulan cihaz, klinik kullanım için tek kullanımlık bir kapsül endoskopi ünitesi içinde hizmet verebilir.



1. INTRODUCTION

Advances in microelectronics and optoelectronics have played a key role in the development of endoscopes, enabling the assessment of unhealthy tissue formation within the gastrointestinal (GI) tract. To improve patient comfort and increase the reach of the imaging procedure to the entire GI, wireless capsule endoscopes (WCE) were developed [2]. Capsule endoscopes are equipped with CMOS / CCD camera(s) to acquire images throughout the GI tract and an antenna unit to transfer the data to the external unit. Yet the images are far from providing cellular resolution and only observe the surface. Tethered capsule endoscopes (TCE) were developed, having optical resolution and multiple depth imaging capabilities, using optical coherence tomography (OCT). While the tether (including electrical and optical connections) limits the ability to access the entire GI tract, these devices have found use in early diagnosis of Esophageal Cancer and Barrett's Esophagus [3,4]. TCEs typically employ a micromotor for circumferential laser scanning. Yet, the power consumption of off-the-shelf micromotors generally is above 50 mW. Moreover, micromotor height (not including the rotating prism on its shaft) is above 10 mm, occupying more than 30% of the available space within a capsule.

Figure 1.1 and Table 1.1 compare various types of circumferential scanning or rotary mechanisms, including MEMS rotary actuators and micromotors (both academic achievements and off-the-shelf components). The comparison is made based on power consumption, frequency, the height of the rotational device, and rotation angle. Performances of the two devices presented in this study are also marked on figures and included in the table.

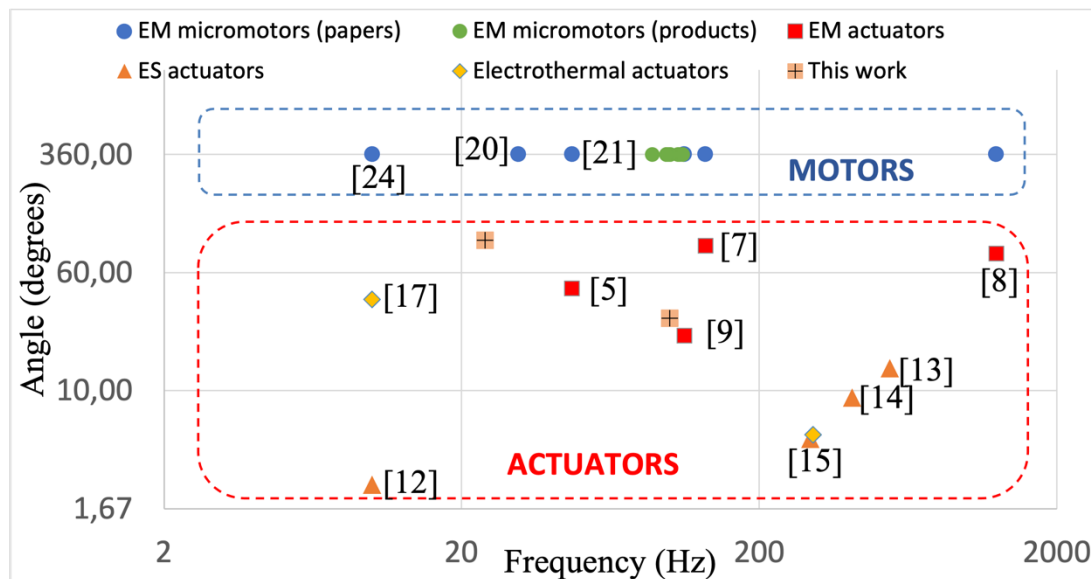


Figure 1.1: All Performance comparisons of micromotors and rotary actuators [1]

We present a 3D-Printed rotary actuator to improve form factor and reduce power consumption manufacturing cost, and time. Our design -illustrated in Fig. 1.2- comprises two cantilevers connected to a rotary shaft via nylon strings. The movement of the cantilevers, achieved with electromagnetic force between an external coil and the magnet at the tip of the cantilever, leads to rotation of the shaft. A prism with a reflective mirror is placed on the rotating body for circumferential scanning of the incoming laser light on the target. The dimensions of the device are given in Table 1.2.

The presented rotary actuator has a reduced form factor (having a height of 7 mm, apart from the assembled prism) in comparison to both off-the-shelf products and studies in the literature. Moreover, the scan angle of the device is superior to the MEMS rotary actuator counterparts. The use of 3D printing in the manufacturing of our device makes it cost-effective, and particularly appealing as a disposable device. The developed electrical circuit analogy, finite element simulations, experimental demonstration of $> 90^\circ$ rotational scan, and design of an in capsule inductor to facilitate actuation are other contributions of this study.

Table 1.1: Rotary actuator and micromotor comparison

Reference Brand/Model	Type	Freq. (Hz)	Optical scan angle (degrees)	Diameter (mm)	Height (mm)	Power (mW)
[5]	Electromag.	-	1.1	6	6	26
[6]	Electromag.	47	47	10	100	60
[7]	Electromag.	-	20	-	-	-
[8]	Electromag.	132	90	0.5	16	450
[9]	Electromag.	1253	80	2	< 1	-
[10]	Electromag.	112	23	7	< 1	31
[11]	Electrostatic	-	2.8	5	5	14
[12]	Electrostatic	-	1.5	1.2	< 1	-
[13]	Electrostatic	10	2.4	1	< 1	-
[14]	Electrostatic	550	14	3	< 1	-
[15]	Electrostatic	410	9	1	< 1	-
[16]	Electrostatic	300	5	4.3	< 1	-
[17]	Electrother.	-	20	1.5	1.5	35
[18]	Electrother.	10	40	4.5	1.5	360
[19]	Electrother.	-	4	< 1	< 1	2230
[20]	Electrother.	300	10	< 1	< 1	10
[21]	Micromotor	31	360	4	20	-
[22]	Micromotor	42	360	-	-	-
[23]	Micromotor	5	360	4	0.25	0.31
[24]	Micromotor	-	360	4	3.6	500
[25]	Micromotor	9	360	55	13	-
[26]	Micromotor	18	360	3	2.5	72
[27]	Micromotor	616	360	22	15	-
[28]	Micromotor	1.25	360	4	5	400
Pelonis PTFF-M20-07170	Micromotor	100	360	10	15	152
Pelonis PTFF-031-12130	Micromotor	108	360	14	20	570
Pelonis PTFS-180sm-1740	Micromotor	107	360	20	32	2340
Jinlong Mach. Z7AL2A000001	Micromotor	111	360	4	10	53
Kinmore Motore FF-K10VA-05220	Micromotor	100	360	8	12	150
Kinmore Motore RF-130H-13225	Micromotor	88	360	16	27	450
Faulhaber 1509B	Micromotor	98	360	15	9	880

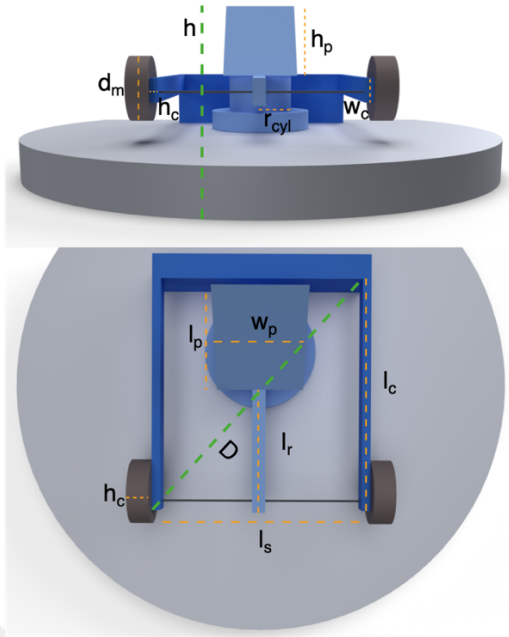


Figure 1.2: CAD drawing of the designed rotary actuator [1]

Table 1.2: Device dimensions [1]

Part	Symbol	Dimension (mm)
Cantilever length	l_c	10.5
Cantilever width	w_c	1.5
Cantilever height	h_c	0.5
Prism length / width	l_p	4
Prism width	w_p	4
Prism height	h_p	4
Magnet diameter	d_m	3
Magnet height	l_c	1
Device width	W	6.5
Device diameter	D	13
Device height	h	8.5 / 7*
String length	l_s	6.5
String radius **	r_s	0.05
Rotary arm length	l_r	6.5
Rotating cylinder radius	r_{cyl}	1.75

* not shown in Fig 2

** with/without prism

In the upcoming sections, we share a circuit equivalent model of the device, finite-element-simulation results, manufacturing, experimental setup, and results. Finally, a discussion is provided on an in-capsule coil design and other aspects to elevate the capabilities of this device for its transition to the clinic.

1.1 3-D Printing Technology

3D printing, also known as additive manufacturing, is a revolutionary technology that allows for the creation of three-dimensional objects from a digital design file. Unlike traditional manufacturing methods that involve subtracting or shaping materials, 3D printing builds objects layer by layer, adding material to form the desired shape. This process offers immense flexibility, enabling the production of complex and intricate designs that may be difficult or impossible to achieve using conventional manufacturing techniques.

Fused Deposition Modeling (FDM) is a type of 3D printing technique that operates by melting and extruding a thermoplastic filament through a heated nozzle. (Fig. 1.3) The nozzle moves in a precise pattern, depositing the molten material layer by layer, ultimately creating a solid object. FDM 3D printers are widely used in various industries and by hobbyists due to their affordability, ease of use, and versatility.

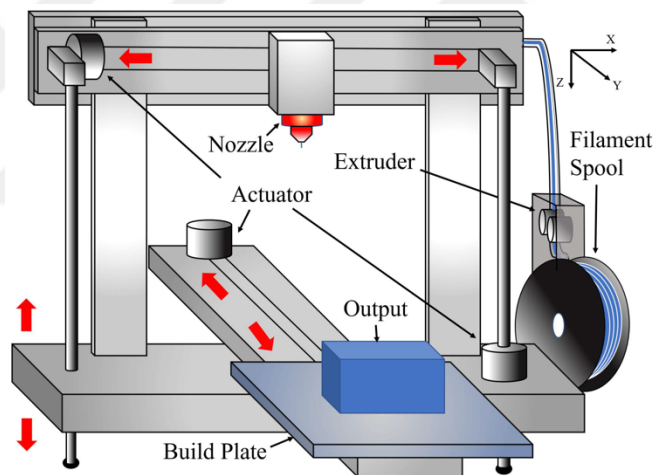


Figure 1.3: Fused Deposition Modelling Illustration [29]

Actuators play a crucial role in converting input signals into physical motion or force. FDM 3D printed actuators utilize the advantages of FDM technology to create custom-designed actuators with specific functionalities. These actuators can be used in a wide range of applications, including robotics, automation, medical devices, and more.

FDM 3D printed actuators offer several benefits. First, the ability to fabricate complex geometries allows for the creation of intricate actuator designs tailored to specific requirements. Second, FDM allows for the integration of multiple components into a single printed part, reducing assembly time and complexity. Additionally, FDM

materials offer a range of mechanical properties, allowing the selection of materials that suit the actuator's intended function.

By leveraging FDM 3D printing, engineers and designers can rapidly prototype and iterate their actuator designs, saving time and costs associated with traditional manufacturing methods. This technology opens up new possibilities for developing innovative actuators with enhanced performance and customization options.¹



¹ This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoglu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”

2. PRELIMINARY WORK

2.1 Modeling

Both cantilevers are modeled using a series resistor – inductor – capacitance (RLC) resonator. The inductor value in the electrical domain corresponds to the mass (m) of the magnet that is attached to the tips of the cantilevers. The capacitance value in the electrical domain corresponds to the reciprocal of the spring constant of the cantilever (k_c), such that [30]:

$$k_c = E_c \frac{w_c h_c^3}{4l_c^3} \quad (1)$$

where E_c is the Young's modulus of the cantilever material (15 MPa for TPU [31], 3.5 GPa for PLA [32]). The cantilevers are then connected to a rotating body with nylon strings. The string is modeled as a clamped-clamped beam, whose spring constant (k_s) can be calculated as [30]:

$$k_s = E_s \frac{16r_s^4}{L_s^3} \quad (2)$$

where E_s is the Young's modulus of nylon (2.7 GPa [33]). A displacement of $2\pi r$ by both cantilevers results in a rotation angle of 2π radians of the rotating body, having a radius of r . The transition between displacement and rotation is modeled with a transformer having an $r:1$ turns ratio. Finally, the rotating body inertia (L_r) is simply modeled based on the inertia of a combined rotating cylinder and rotating arm as:

$$k_s = E_s \frac{16r_s^4}{L_s^3} \quad (3)$$

where, m_{cyl} (143 mg) and m_r (6 mg) are the masses of rotating body (including the mass of the prism and rotating cylinder) and the rotating arm; respectively. The circuit equivalent of the rotary actuator is illustrated in Figure 2.1, and the circuit element values calculated based on the above equations are tabulated in Table 2.1. The resistance values representing the losses are assigned to give a quality factor of $Q \approx 10$. Figure 2.2 shows the simulation results of the rotary actuator, where the resonance frequencies were observed as 16 Hz and 265 Hz, respectively, for TPU and PLA materials.

Table 2.1 : Element values for the circuit model [1]

Circuit element	Symbol	Mechanical equivalent	Value
Capacitance (cantilever)	C_c	k_c^{-1}	3.05 F (PLA) 13 mF (TPU)
Inductance (cantilever)	L_c	Effective mass of cantilever (\cong mass of magnet)	54 μ H
Resistance (cantilever)	R	Damping	0.5 $\mu\Omega$
Capacitance (string)	C_s	k_s^{-1}	2.7 F (nylon)
Inductance (rotating body)	L_r	Moment of inertia of rotating body	0.635 nH

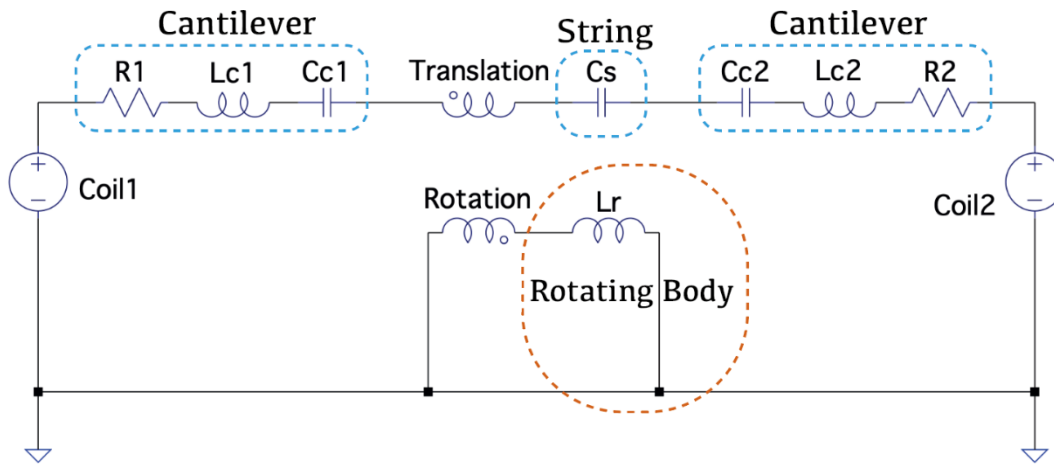


Figure 2.1: Circuit equivalent model of the proposed rotary actuator [1]

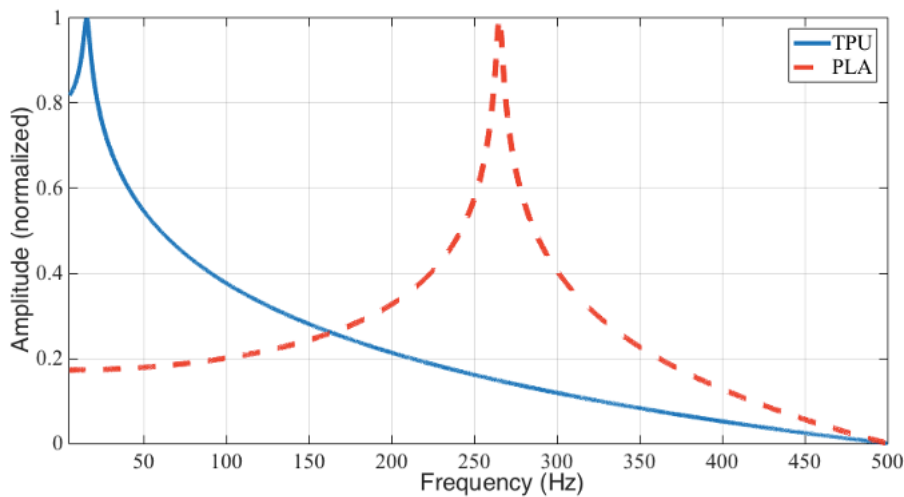


Figure 2.2: Frequency response (normalized) observed by the proposed circuit model for TPU- and PLA-based rotary actuators. [1]

2.2 Simulations

The fundamental vibration mode of the device was investigated using Finite-Element-Analysis (FEA) with ANSYS software. (Fig. 2.3) Figure 2.4 illustrates the mode shape and different instances of the mode. The fundamental mode frequency of 18 Hz for TPU and 245 Hz using PLA was found using FEA. The simulation results validate our circuit model. We have included a table in the results section, comparing the mode frequency findings from our model, simulations, and experiments.

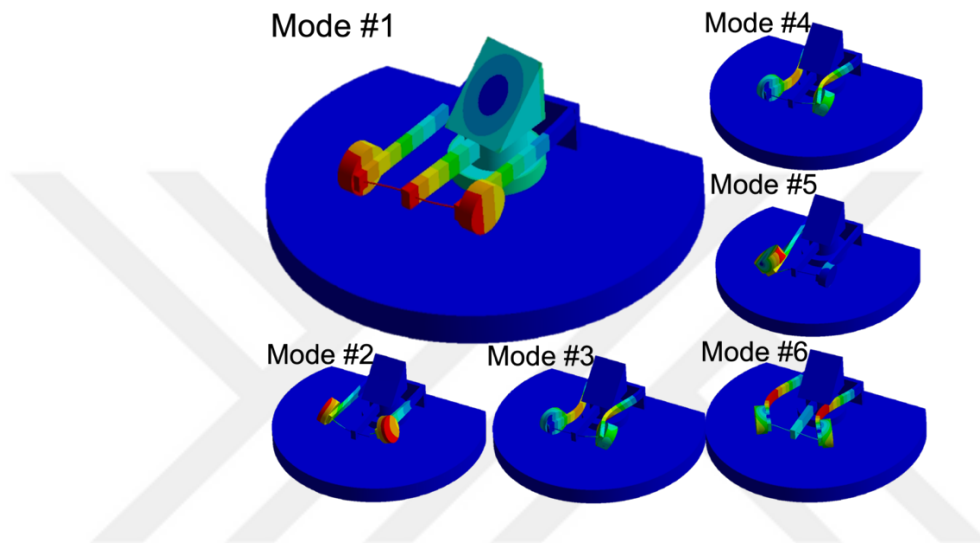


Figure 2.3: Device resonance modes [1]

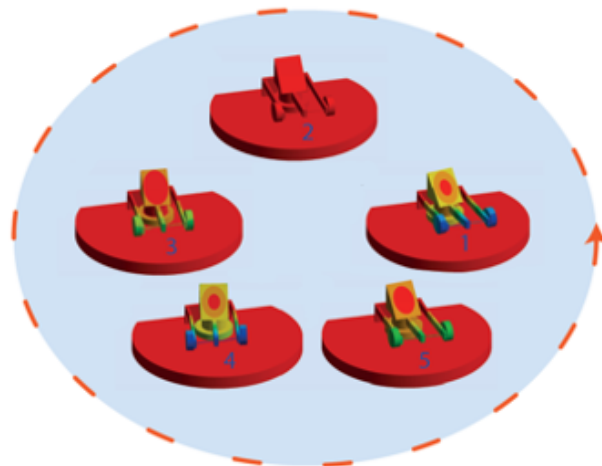


Figure 2.4: Different instances of the fundamental rotary mode (18 Hz for TPU and 245 Hz for PLA) of the proposed device. ²

² This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoglu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”



3. MANUFACTURING

The presented rotary actuator was 3D-printed in a modular fashion, using Fused Deposition Modeling (FDM). (Fig. 3.1) Figure 3.2 illustrates the manufacturing and integration steps. Initially, the cantilevers, rotating platform, and the prism are printed. A gold-coated silicon mirror is attached to the prism, neodymium magnets are attached (via epoxy) to the distal ends of the cantilevers, and the cantilevers are attached to the rotating body via a nylon string. The entire platform is embedded in a 25 mm cylinder for integration with conventional optomechanical holders. Yet the active part spans a diameter of 13 mm that is compatible with capsule endoscope dimensions.

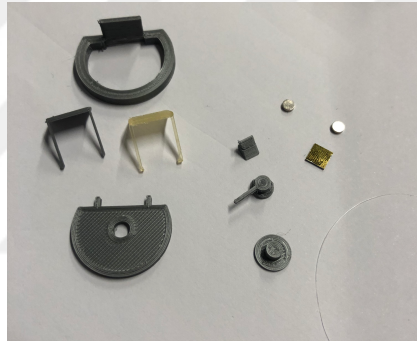


Figure 3.1: Manufactured parts of the rotary actuator with external parts

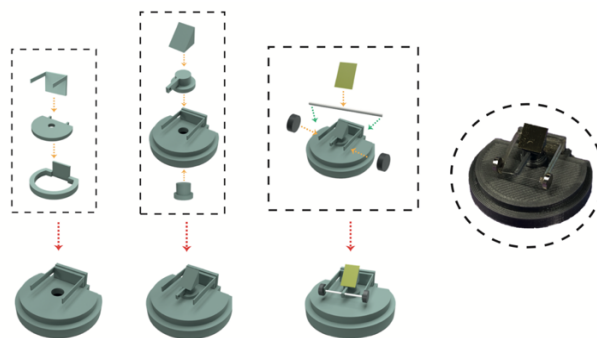


Figure 3.2: Manufacturing and assembly steps of the developed rotary actuator [1]³

³ This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoğlu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”



4. EXPERIMENTAL SETUP

The manufactured scanners were characterized using the setup illustrated in Figure 4.1. Two external 100 mH coils were used for electromagnetic actuation, driven out-of-phase to facilitate maximum rotation. A laser diode (Thorlabs CPS635F) was directed towards the prism, and the scan angle was measured based on the length of the scan line on the target screen and the distance to the target screen. The frequency was swept to acquire the transfer function for both PLA and TPU rotary actuators. Experimental results are given in Figure 4.2.

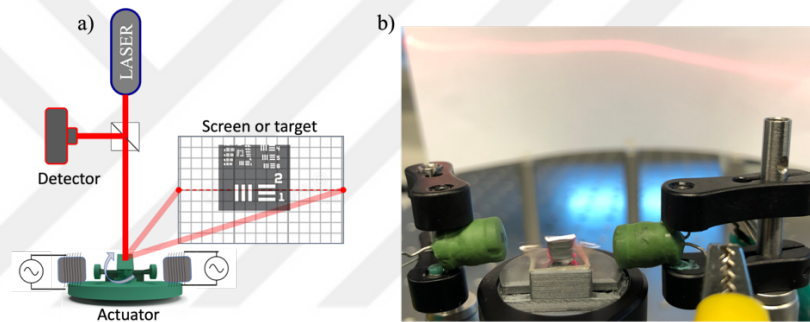


Figure 4.1: Experimental setup a) sketch b) laboratory demonstration. [1]

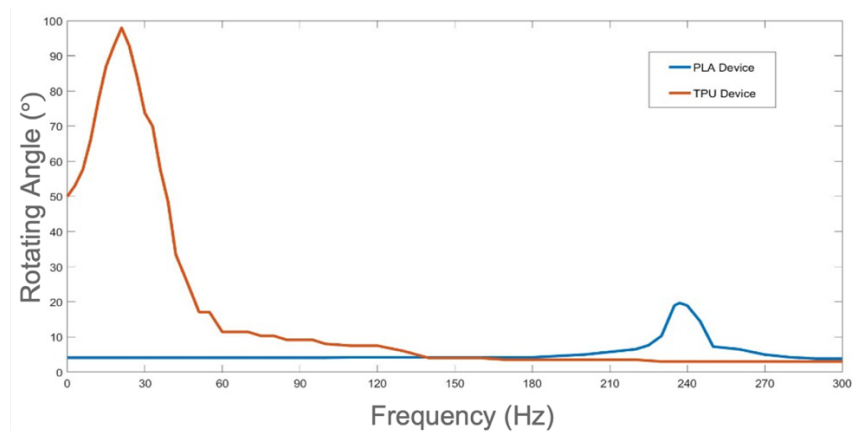


Figure 4.2: Experimental results⁴

⁴ This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoğlu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”



5. RESULTS

The experimental resonances were observed as 237 Hz for the PLA and 21 Hz for the TPU devices, in line with our analytical model and the simulations, as shown in Figure 5.1, along with the resonance values inferred from analytical modeling. A total scan angle of 98° was measured for the TPU rotary actuator and 20° for the PLA rotary actuator. The maximum scan angle is observed when a total of 200 mW power is delivered to the inductors for both TPU- and PLA-based devices. Based on the acquired scan angles we predict a magnetic force of 0.3-20 mN to facilitate the reported scan angles (via finite-element calculations and analytical calculations based on Hooke's Law) for TPU and PLA devices, respectively. The difference between force values for TPU and PLA devices rise due to the fact that a larger distance between the magnets and the external coils were set for TPU devices to prevent collapse.

Table 5.1 tabulates the fundamental frequencies found using the circuit model, FEM simulation, and experiments, showcasing a good match between results.

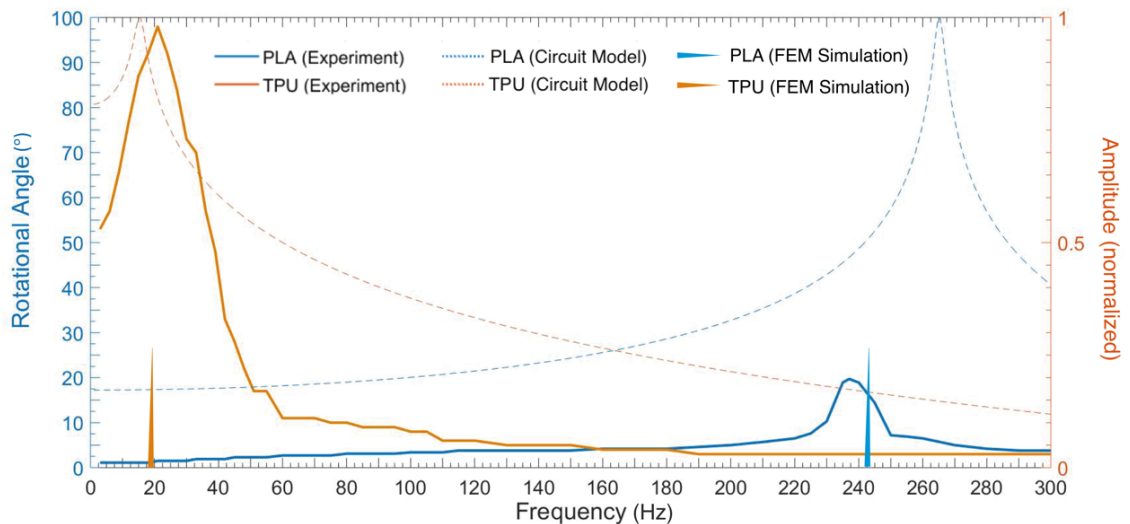


Figure 5.1: Frequency response of the rotary actuator [1]

Table 5.1: Fundamental mode frequency comparison of the developed circuit model, FEM, and measurements

	Circuit Model	FEM Simulation	Experiment
TPU-based Actuator	16 Hz	19 Hz	21 Hz
PLA-based Actuator	265 Hz	245 Hz	237 Hz

Next, we placed a United States Air Force (USAF) target and measured the cross section from Group 2 Element 1 through observing the back reflected light with a photodetector unit (Thorlabs PDA36A). (Fig. 5.2) Figure 5.3 illustrates the acquired light intensity as a function of time, from Group 2, Element 1 of the USAF target, that well-matches the opaque-transparent line pairs of the target itself.

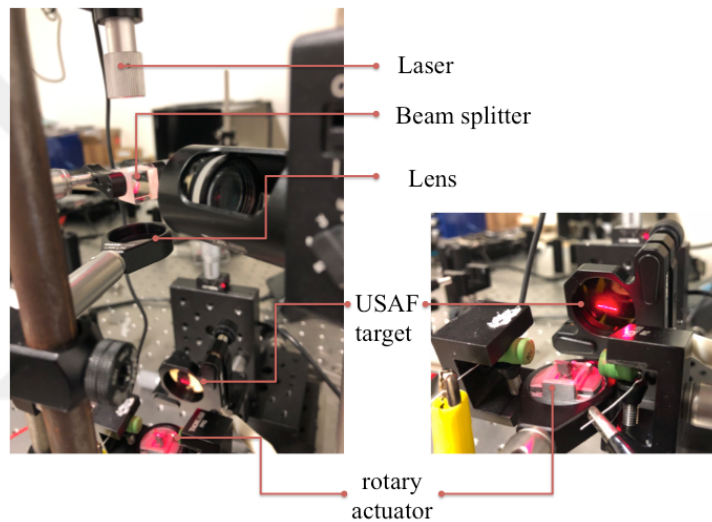


Figure 5.2: Imaging setup [1]

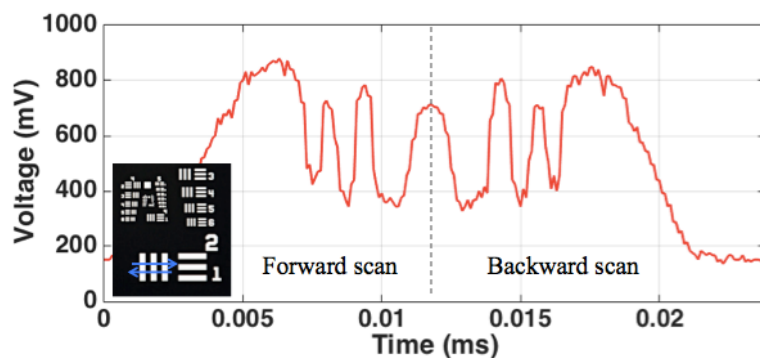


Figure 5.3: Photodetector output [1]⁵

⁵ This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoğlu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”

6. CONCLUSION

We presented a 3D-printed rotary actuator for scanning capsule endoscopy. The electromagnetically actuated rotary device is composed of two out-of-phase driven cantilevers connected to a rotating body. We developed electrical equivalent circuit models and conducted finite element simulations, which are both in line with the experimented modal frequencies of 21 Hz for TPU and 237 Hz for PLA scanner. We obtained a total scan angle of 20° for the TPU and 98° for the PLA device. With the use of a reflective pyramid on the rotating body and the integration of four photo-detectors, one can achieve a full circumferential scan. Overall, the presented device having a height of 7 mm, compares favorably over micromotors in terms of form factor and is comparable in terms of power consumption. Furthermore, the rotary device is favorable in terms of total optical scan angle over MEMS rotary devices. It is noteworthy that 3D printing is an appealing technology for producing disposable actuators for medical devices, in terms of cost and manufacturing speed.⁶

⁶ This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoğlu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”



7. FUTURE WORK

7.1 Horse-shoe Coil

The experiments involve the employment of external coils. In a clinical capsule endoscope, one would have to embed the coils within the capsule. Below, we provide a conformal coil design for use within the capsule. The designed coil is configured as a horseshoe-shaped, semi-toroid form having a 13 mm diameter.

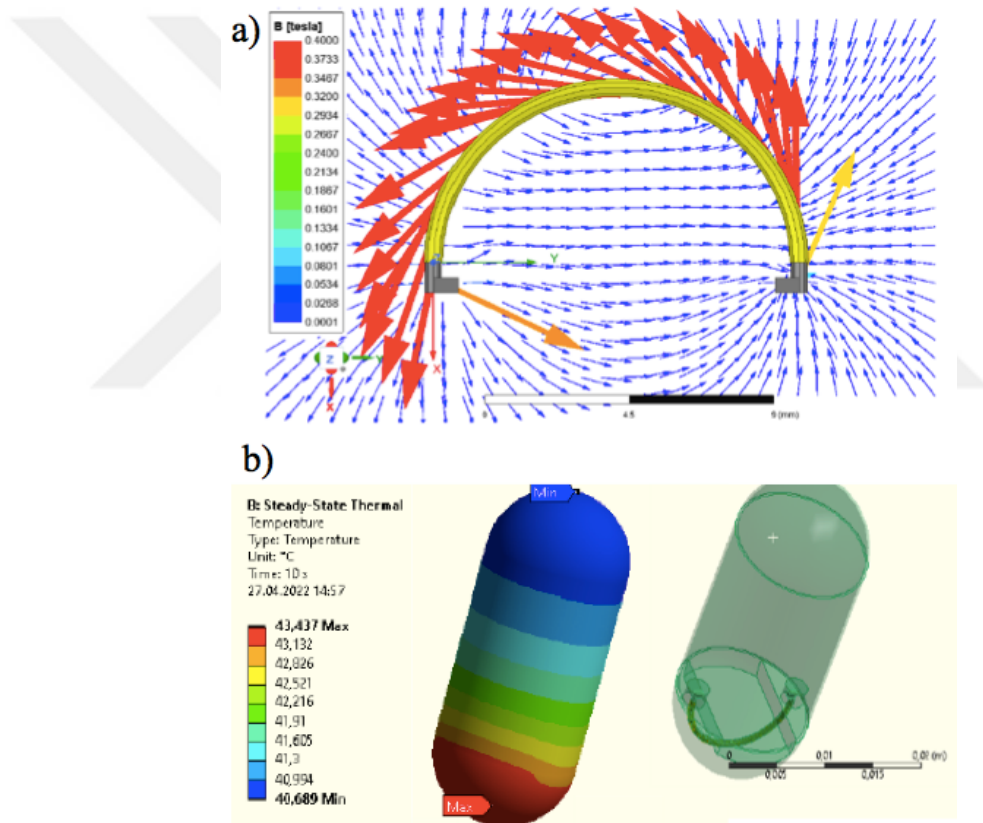


Figure 7.1: Magnetic field and temperature simulations of the designed conformal coil for use in the actuation of the presented rotary device. [1]

We assume a core permeability of $\mu_r = 3000$ core, a copper coil having $50 \mu\text{m}$ diameter with 7000 windings on the core having 0.5 mm cross-sectional diameter. Figure 7.1.a illustrates simulation results for the designed coil in the ANSYS simulation environment, where we observe an inductance of 100 mH , like the discrete inductor used in the experiments. The generated maximum magnetic field is simulated as 27

mT for a coil rms current of 7 mA, which is once again comparable to the measured magnetic field of 7 mTs for the experimented discrete inductors under the same current.

7.2 Thermal Insulation

Moreover, the heat simulation results (Fig. 7.2.b) inside the capsule reveal a temperature increase up to 43 °C at the surface for the given drive current. Note that ceramic insulators were utilized in the heat simulations to isolate the heat load from the surface of the capsule. Overall, based on the observed magnetic field levels, we expect the designed coil to provide adequate force to reach the scan angles experimentally observed using external coils. Note that a pyramid structure may be utilized instead of a prism on the rotary actuator to quadruple the scan angle for fully circumferential scanning. The use of multiple reflective surfaces, as in the pyramid, would require various detectors to monitor the data arriving from each surface of the pyramid (i.e., a pyramid with 4 surfaces and 4 photodiodes would be able to accomplish a full circumferential scan of 360 ° when the rotary actuator rotates by 90°).⁷

⁷ This chapter based on the journal paper “E. Tekin, A. C. Erten, M. B. Yelten and O. Ferhanoglu (2023) A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy, IEEE Photonics Technology Letters, vol. 35, no. 16, pp. 891-894, doi: 10.1109/LPT.2023.3285273.”

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APPENDICES

APPENDIX A: Early Cantilever Designs



APPENDIX A: Early Cantilever Designs

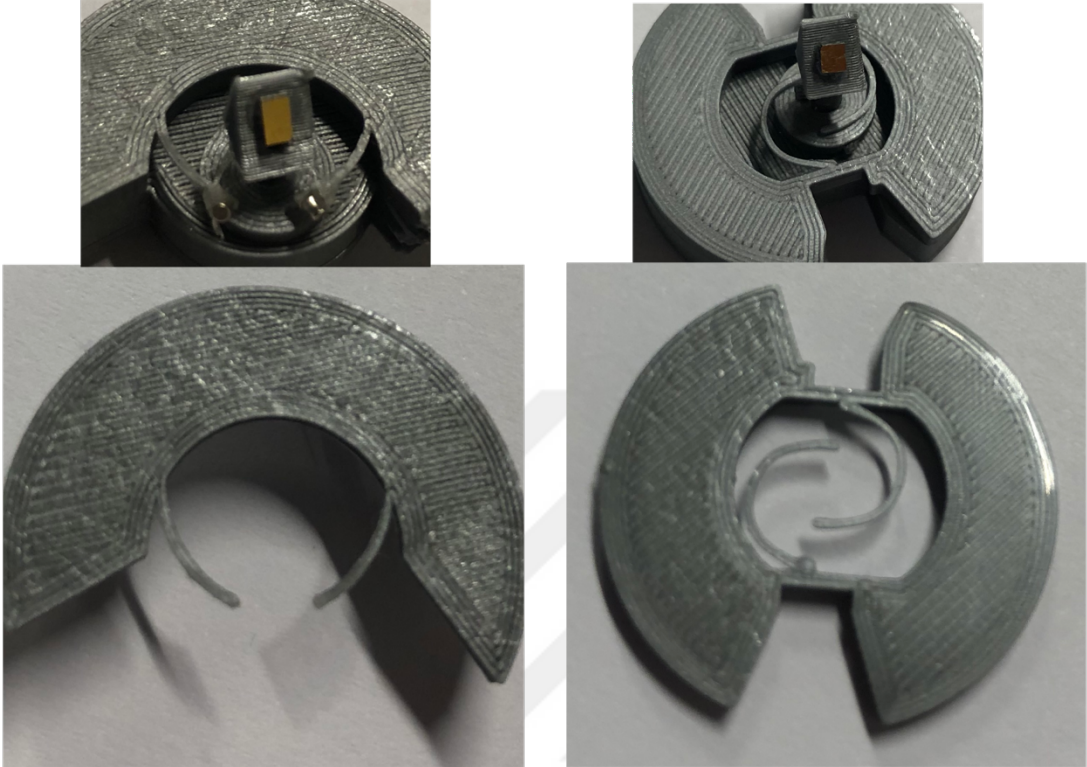
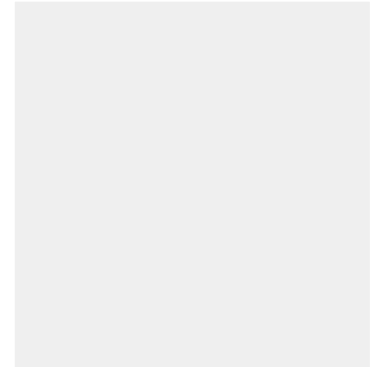


Figure A.1: Early Cantilever Designs

CURRICULUM VITAE

Name Surname : Engincan Tekin



EDUCATION :

- **B.Sc.** : 2020, Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Department of Electrical and Electronics Engineering

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Tekin, E.** 2022. A 3D Printed Rotational MEMS Actuator for Scanning Capsule Endoscopy, 2022 INTERNATIONAL CONFERENCE ON OPTICAL MEMS AND NANOPHOTONICS (OMN) , 2022 (Oral Presentation)
- **Tekin, E.** 2023. A Resonant Pulley Rotary Actuator for Scanning Capsule Endoscopy." IEEE Photonics Technology Letters

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- **Tekin, E.** 2019. Quantitative Measurement of Colorimetric Signals in 180nm Standard CMOS Technology, 2019 11th International Conference on Electrical and Electronics Engineering (ELECO)
- **Tekin, E.** 2020. Quantitative detection system for immunostrips in 180nm standard CMOS technology. Analog Integr Circ Sig Process 106, 493–500
- **Tekin, E.** 2023. In-Situ Measurement of Anisotropic Youngs Modulus in Fused Deposition Modelling Printed Cantilever, Journal of Micromechanics and Microengineering