JOURNAL OF DATA-DRIVEN ENGINEERING SYSTEMS

Development of a Real-Time Position Tracking System for Remote-Controlled Drug-Delivery Capsules Using Dual Magnetic Vector Detection

Aviad Iddan[1]*, Azer Zamir [2], Sabah Moren [3], Mooshe Natanail [3]

[1] Sentinelle Medical, Inc., Toronto, ON M5V 3B1, Canada
[2] Given Imaging Ltd., Building 7, New Industrial Park, Yoqneam 20692, Israel
[3] Sentinelle Medical, Inc., Toronto, ON M5V 3B1, Canada

(Received: 17th December 2022; Accepted: 18th January 2023; Published on-line: 19h February 2023)

Abstract

This study presents a theoretical basis for the construction of a real-time position tracking system designed for remote-controlled drug-delivery capsules, allowing precise drug delivery to specific locations within the gastrointestinal tract. The tracking system utilizes dual magnetic vector detection, employing two distinct sets of magnetic field sensing devices. One set detects the externally excited alternating magnetic field with specific frequencies, while the other measures the geomagnetic field. A mathematical model is developed based on the Biot–Savart law, incorporating the earth's magnetic field and quaternion rotation theory to compensate for the dynamic spatial orientation of the capsule during traversal through the gastrointestinal tract. The proposed model employs an improved artificial bee colony algorithm to solve the inverse magnetic field problem. The algorithm incorporates chaotic sequencing to enhance initial solution diversity and implements a ranked selection strategy. To expedite convergence, the Levenberg-Marquardt algorithm is introduced in later stages. A prototype of the tracking system is constructed and verified, yielding a convergence rate of 100% with an average of 179 iterations. Prototype testing demonstrates that the dual magnetic vector detection method simplifies the solution of the inverse magnetic field problem, reduces tracking time for each data round, and enhances solution accuracy.

Keywords: Drug-Delivery Capsule, Position Tracking System, Gastrointestinal Tract, Magnetic Vector Detection, Quaternion Rotation Theory, Artificial Bee Colony Algorithm

I. Introduction

In recent years, there has been a notable increase in the prevalence of chronic digestive tract illnesses. This rise can be attributed to the fast-paced nature and heightened stress levels of modern life. Unfortunately, these illnesses pose a significant challenge to treatment, particularly with oral medications. Often, these medications fail to reach the affected tissues in sufficient doses, thereby limiting their effectiveness. However, a potential solution lies in delivering drugs directly to the specific sites of inflammation, wounds, or lesions within the gastrointestinal tract. Such targeted drug delivery would enhance absorption at the intended area, reduce the occurrence of side effects, and ultimately improve the overall efficacy of treatment [1-2].

Presently, the primary method for acquiring images of the gastrointestinal tract involves capsule endoscopy. However, an innovative alternative can be explored: the development of a capsule equipped with remote-controlled drug delivery capabilities, rather than a traditional camera. This capsule would enable the precise administration of drugs at specific points along the gastrointestinal tract. Once the capsule reaches the desired target site, external control equipment would command the release of drugs. Consequently, accurate and real-time tracking of the capsule's position within the gastrointestinal tract becomes a crucial requirement for such a system [3-4].

While certain medical imaging techniques, including X-ray, ultrasound, and magnetic resonance imaging, provide visual information about the capsule's location through images, they do not offer precise parameters of position and orientation necessary for feedback data in actuation systems. In this context, magnetic tracking methods present themselves as a promising solution. Specifically, the utilization of a permanent magnet enclosed within the in vivo micro-device offers a low-cost method that enables continuous tracking. However, these methods encounter limitations concerning solution speed and tracking range. Particularly, the magnetic tracking method utilizing static magnetic fields faces interference between the

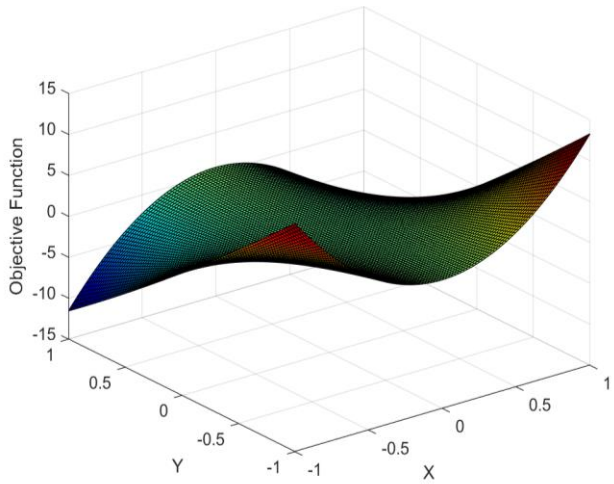

Fig. 9. 3D Plot of Objective Function without Hyperparameters

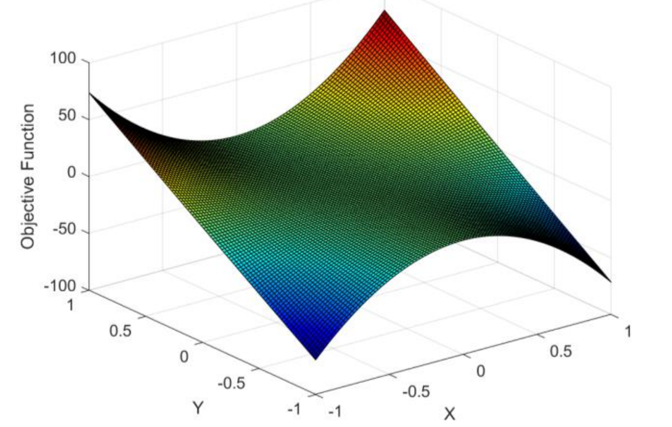

Fig. 10. 3D Plot of Objective Function with Hyperparameters

VI. Conclusion

This research proposed a method called dual magnetic vector detection, which allows for real-time tracking of drug-delivery capsules in the gastrointestinal tract. To validate the method, a prototype tracking system was designed and developed. The tracking model utilized a small number of generation coils to excite magnetic fields and had only three unknown quantities, simplifying the design and reducing the amount of sample data needed. To solve the inverse magnetic field problem, a ranked selection chaotic bee colony method in combination with the LM algorithm was employed. The chaotic sequence provided a better initial solution set compared to the random sequence used in the standard algorithm, and the ranked selection strategy prevented premature entrapment at a local extreme value. Additionally, the LM algorithm expedited convergence at later stages. Through algorithm simulations and prototype verification, it was demonstrated that the dual magnetic vector measurement method effectively tracked the position of the target. The utilization of quaternion rotation in the tracking model improved its simplicity, accuracy, and solvability. This study establishes a theoretical foundation and serves as an initial reference for tracking remote-controlled gastrointestinal intervention equipment. The next phase of development involves miniaturizing and integrating the equipment into capsules for real-world testing.

REFERENCES

[1] Ciuti G, Menciassi A, Dario P. Capsule endoscopy: from current achievements to open challenges. IEEE reviews in biomedical engineering. 2011 Oct 10;4:59-72.

[2] Chan M, Estève D, Fourniols JY, Escriba C, Campo E. Smart wearable systems: Current status and future challenges. Artificial intelligence in medicine. 2012 Nov 1;56(3):137-56.

[3] Sitti M, Ceylan H, Hu W, Giltinan J, Turan M, Yim S, Diller E. Biomedical applications of untethered mobile milli/microrobots. Proceedings of the IEEE. 2015 Feb;103(2):205-24.

[4] Taylor RH, Menciassi A, Fichtinger G, Fiorini P, Dario P. Medical robotics and computer-integrated surgery. Springer handbook of robotics. 2016:1657-84.

[5] Steiger C, Abramson A, Nadeau P, Chandrakasan AP, Langer R, Traverso G. Ingestible electronics for diagnostics and therapy. Nature Reviews Materials. 2019 Feb;4(2):83-98.

[6] Cheraghifard M, Taghizadeh G, Akbarfahimi M, Eakman AM, Hosseini SH, Azad A. Psychometric properties of Meaningful Activity Participation Assessment (MAPA) in chronic stroke survivors. Topics in Stroke Rehabilitation. 2021 Aug 18;28(6):422-31.

[7] Amini M, Hassani Mehraban A, Pashmdarfard M, Cheraghifard M. Reliability and validity of the Children Participation Assessment Scale in Activities Outside of School–Parent version for children with physical disabilities. Australian Occupational Therapy Journal. 2019 Aug;66(4):482-9.

[8] Yang SY, Sencadas V, You SS, Jia NZ, Srinivasan SS, Huang HW, Ahmed AE, Liang JY, Traverso G. Powering implantable and ingestible electronics. Advanced functional materials. 2021 Oct;31(44):2009289.

[9] Kalantar-Zadeh K, Ha N, Ou JZ, Berean KJ. Ingestible sensors. ACS sensors. 2017 Apr 28;2(4):468-83.

[10] Cheraghifard M, Shafaroodi N, Khalafbeigi M, Yazdani F, Alvandi F. Psychometric properties of the Persian version of Volitional Questionnaire in Patients with Severe Mental Illnesses. Journal of Rehabilitation Sciences & Research. 2019 Jun 1;6(2):86-90.

[11] Ciuti G, Skonieczna-Żydecka K, Marlicz W, Iacovacci V, Liu H, Stoyanov D, Arezzo A, Chiurazzi M, Toth E, Thorlacius H, Dario P. Frontiers of robotic colonoscopy: a comprehensive review of robotic colonoscopes and technologies. Journal of clinical medicine. 2020 May 31;9(6):1648.

[12] Charthad J, Weber MJ, Chang TC, Arbabian A. A mm-sized implantable medical device (IMD) with ultrasonic power transfer and a hybrid bi-directional data link. IEEE Journal of solid-state circuits. 2015 May 18;50(8):1741-53.

[13] M. Izadi, M. Jabari, N. Izadi, M. Jabari, and A. Ghaffari, "Adaptive Control based on the Lyapunov Reference Model Method of Humanoid Robot Arms using EFK," in 2021 13th Iranian Conference on Electrical Engineering and Computer Science (ICEESC), 2021.

[14] Simaan N, Yasin RM, Wang L. Medical technologies and challenges of robot-assisted minimally invasive intervention and diagnostics. Annual Review of Control, Robotics, and Autonomous Systems. 2018 May 28;1:465-90.

[15] Than TD, Alici G, Zhou H, Li W. A review of localization systems for robotic endoscopic capsules. IEEE transactions on biomedical engineering. 2012 Jun 18;59(9):2387-99.

[16] N. Izadi, M. Jabari, M. Izadi, M. Jabari, and A. Ghaffari, "Optimal Path Design for a Flexible Rigid Two-Bar Robot in Point-to-Point Motion," in 2022 14th Iranian Conference on Electrical Engineering and Computer Science (ICEESC), 2022.

[17] P. Gaderi Baban, Y. Naderi, G. Ranjbaran, and S. Homayounmajd, "Control of delayed nonlinear model of type 1 diabetes using an improved sliding model strategy," Journal of Bioengineering Research, vol. 3, no. 3, pp. 8-15, 2021.

[18] Iakovidis DK, Koulaouzidis A. Software for enhanced video capsule endoscopy: challenges for essential progress. Nature Reviews Gastroenterology & Hepatology. 2015 Mar;12(3):172-86.

[19] Ranibaran G, Moin MS, Alizadeh SH, Koochari A. Analyzing effect of news polarity on stock market prediction: a machine learning approach. In2021 12th International Conference on Information and Knowledge Technology (IKT) 2021 Dec 14 (pp. 102-106). IEEE.

[20] Troccaz J, Dagnino G, Yang GZ. Frontiers of medical robotics: from concept to systems to clinical translation. Annual review of biomedical engineering. 2019 Jun 4;21:193-218.

[21] Stauss S, Honma I. Biocompatible batteries—materials and chemistry, fabrication, applications, and future prospects. Bulletin of the Chemical Society of Japan. 2018 Mar 15;91(3):492-505.

[22] B. Goudarzi, A. Savabkar, M. Serajchi, and M. Haghighatseresht, "Identification of Electrohydrodynamic Printer and designing ADRC Control with Extended Observer," in 2022 14th Iranian Conference on Electrical Engineering and Computer Science (ICEESC), 2022.

[23] Najari, A., Shabani, F. and Hosseynzadeh, M., 2021. INTEGRATED INTELLIGENT CONTROL SYSTEM DESIGN TO IMPROVE VEHICLE ROTATIONAL STABILITY USING ACTIVE DIFFERENTIAL. Acta Technica Corviniensis-Bulletin of Engineering, 14(1), pp.79-82.

[24] van Wijck K, Lenaerts K, Grootjans J, Wijnands KA, Poeze M, Van Loon LJ, Dejong CH, Buurman WA. Physiology and pathophysiology of splanchnic hypoperfusion and intestinal injury during exercise: strategies for evaluation and prevention. American journal of physiology-gastrointestinal and liver physiology. 2012 Jul 15;303(2):G155-68.

[25] Bergeles C, Yang GZ. From passive tool holders to microsurgeons: safer, smaller, smarter surgical robots. IEEE Transactions on Biomedical Engineering. 2013 Dec 5;61(5):1565-76.

[26] Liu C, Guo YX, Xiao S. Circularly polarized helical antenna for ISM-band ingestible capsule endoscope systems. IEEE Transactions on Antennas and Propagation. 2014 Oct 20;62(12):6027-39.

[27] Beardslee LA, Banis GE, Chu S, Liu S, Chapin AA, Stine JM, Pasricha PJ, Ghodssi R. Ingestible sensors and sensing systems for minimally invasive diagnosis and monitoring: the next frontier in minimally invasive screening. ACS sensors. 2020 Mar 11;5(4):891-910.