Cognitive Insect-Bot Hybridization and Prosthetic Muscle Enhancement in Cyborg Insects

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***Abstract* - The concept of dynamic muscle augmentation in cyborg insects integrates biological adaptability with engineered precision, providing new avenues in robotics. This research improves the control of insect movement through electrical stimulation techniques, such as biphasic waveforms, which reduce tissue damage and provide accurate and consistent locomotion. By deploying the insects' capabilities, such as their energy-efficient mobility and intrinsic ability to navigate around obstacles, together with lightweight on-board electronics, these bio-hybrids accomplish more than small-scale robots in difficult environments. The work also presents swarm algorithms that are an inspiration from collective behaviors for self-navigating complex terrains by these augmented insects. Integrating low-power infrared cameras and image classification systems together with human detection enhances the practical applications of these bio-hybrids in disaster response and environmental monitoring. This would lower the energy usage and keep functionality intact, making the cyborg insects suitable for search missions. The research, in this case, harmonizes the instinctive behavior of the insects with the control algorithms, which helps in mitigating some of the problems that biological variability poses. Long-term operability is ensured through charge-balanced electrical stimulation, and it highlights the potential for sustainable and adaptable systems. These results establish cyborg insects as a novel solution to the limitations of robotics and, thus, offer an efficient, diverse platform for complex real-world applications.**

***Index terms* -- Cyborg Insect, locomotion, Bio-hybrids, Prosthetic Muscle, Cognitive insect-bot**

INTRODUCTION

CYBORG insects refer to the fusion of living organisms with advanced robotic technology and excites a very fast increase in robotics and bioengineering, which primarily includes the living organism such as insects integrated along with miniature electronic systems for the creation of highly adaptive and efficient bio-hybrid robots. Some of the likely applications of cognitive insect-bot fusion-simply linking insects' cognition with that of machines-related to search and rescue, environmental monitoring, and military reconnaissance missions. The cyborg system is applying the natural behavior of the insects and its sensory capabilities complemented with technical hardware to perform tasks which otherwise seem very challenging or impossible for traditional machines [1][2].

The idea of cyborg insects was first conceptualized in the early 2000s, whereby researchers began attaching microelectronic devices to living insects, enabling them to control their movements via electrical stimulation. This early research concentrated more on exploiting the natural capabilities of insects for controlled tasks like navigation and obstacle-avoidance maneuvers. Over time, the field has evolved with depth and even developed dynamic muscle augmentation systems much more advanced than those earlier stages. The artificial devices represent integration through mean electronic backpacks, inertial measurement units, and artificial limbs that complement an insect's natural musculature in terms of mobility and control [3][4].

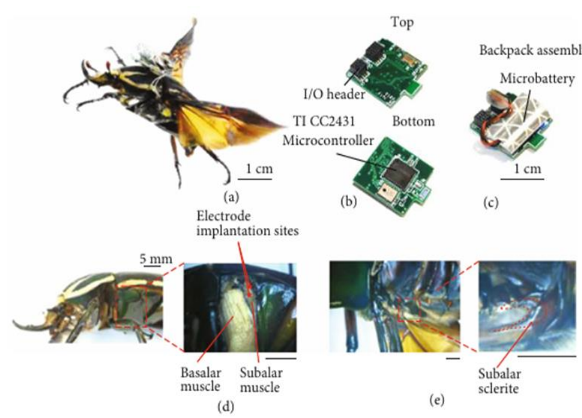

Fig.1. Cyborg and Bionic Systems [2]

Recent advances in the field of cyborg insect research have moved beyond the mere actuation for simple straightforward movement control and now include machine learning algorithms and real-time data processing to enable complex, task-based autonomy by cyborg insects. Dynamic augmentation of muscles through electrical stimulation of certain groups can provide great control over an insect's flight or locomotion, for example. It has been said that muscle stimulation, such as that in the subalar muscles, is better in the control of the elevation and braking motion of this insect in flight. The method has significantly improved the agility and efficiency of these insects as cyborgs that have great potential for their use in MAVs whereas MAVs are suffering from the limitations of weight and energy consumption [5][6].

Real-time feedback control and cognitive sensing systems are further integrated with the cyborg insects to make them even more adaptable. For instance, in search-and-rescue applications, scientists have constructed various systems so that one might easily imagine the concept of a cyborg cockroach made from a backpack with wireless sensors that could make it navigate itself through hard and obstructed terrains to detect the presence of a human with infrared cameras or even make a change in movement based on data obtained from their surroundings. All of these abilities are largely sown by what has been created in terms of advancements in machine learning. This consistently lets the cyborg insects find what can improve or impair the performance by viewing the process of interaction of the environment degrading or enhancing performance. Developing improvement, a learning-driven evolution in the behaviour of insects, becomes the key to building further smarter and more independent systems for bio-hybrid mechanisms [7][8].

Fig.2. Cyborg insect locomotion assistance using bio-inspired 3Dprinted artificial limb [1]

Besides this, non-invasive augmentation methods, like wearable organic solar cells, enabled the integration of power sources into the insect without impairing their operational range and functionality. These developments point to bio-hybrid systems in which the synergy established between natural biological systems and artificial technologies allows new forms of dynamic augmentation of muscles by enhancing endurance and adaptability under real-world conditions [9]. Furthermore, recent efforts on research also focused on developing the insect's cognitive capacity through sensory and control systems integrated within their neural circuitry. Such developments help control more sophisticated insects' behavior, for instance, decision-making capabilities, negotiation with obstacles, and human detection. The integration of biological cognition with robotic enhancement results in a very efficient and versatile system, capable of completing tasks that may otherwise be very difficult for larger machines of higher complexity [10].

This summary thus states that the union of living insects with robotics technology, through cognitive insect-bot fusion and dynamic muscle augmentation frameworks, is a promising approach for the development of highly efficient adaptive robots. With further research in this direction, it is likely that cyborg insects will find applications in all walks of life- including search and rescue applications and environmental monitoring applications perhaps even military. This ability, combined with the biological power and mobility of insects, makes them a unique and powerful tool for the development of the next generation of autonomous systems [11][12].

LITERATURE REVIEW

A promising innovation in the field of bio-hybrid robotics is the integration of biological organisms with advanced technologies, which is a revolution in the field. Here, cyborg insects stand out as a promising innovation because such hybrid systems use the natural capabilities of insects, including agility and adaptability, along with cutting-edge electronics and control systems. This has been applied in various sectors such as search and rescue missions, environmental monitoring, and surveillance.

One of the most significant areas of progress has been the creation of hybrid swarms of cyborg insects. Merging the instinctual ability of insects to navigate and advanced algorithms, researchers created systems that can navigate the most complex and obstacle-laden terrains. For example, the experiments reported in [1] showed the effectiveness of cyborg insect swarms in performing coordinated tasks within dynamic environments. These systems use machine learning to optimize movement and thus increase search efficiency and adaptability in challenging conditions [5,16]. Such advancements make cyborg insects particularly suitable for scenarios where traditional robotic systems would struggle, such as disaster sites or dense forested areas. In the domain of Micro Aerial Vehicles (MAVs), the flight capabilities of insects have been utilized to achieve precise control through stimulation of specific muscles.

Researchers have been able to stimulate subalar muscles in beetles, thus enabling sophisticated maneuvers such as braking and altitude adjustments. This is a new approach in MAV design [10,11]. Such innovations have inspired bio-inspired MAV systems that emulate the flight dynamics of insects, thus leading to more energy-efficient and agile maneuverability. In addition, non-invasive techniques, such as using ultraviolet light combined with fuzzy deep learning systems, have shown high success in modulating moth flight behavior [17]. Such methods are non-invasive and bring the dual advantage of preserving the integrity of the insect while also allowing for complex control. Cyborg insects have emerged as particularly effective tools in urban search and rescue missions because of their ability to navigate unstructured terrains. Equipped with lightweight sensors, thermal imaging systems, and bio-inspired designs, these systems have demonstrated their ability to detect the presence of humans and obstacles with reasonable efficiency [3,13]. For example, experiments using cyborg cockroaches with thermal navigation algorithms have demonstrated that it is possible to locate survivors within a low-visibility disaster scenario, such as a collapsed building or mine shaft [15]. Sustainable power sourcing for the cyborg system is another fundamental area of investigation. Uplighting organic solar cells onto insects with minimum weight can be an ideal power supply that does not conflict with its natural movements in the habitat [20]. Cyborg insect systems thus make long endurance missions feasible without much degradation in remote locations or hazards. Furthermore, improvements are now available in regard to power-saving characteristics related to on-board sensor operations as well as control system applications.Sophisticated mechanisms in the control have also developed, enhancing the reliability of locomotion in cyborg insects.

Charge-balanced biphasic electrical stimulation minimizes tissue damage with movement control enhancement [6]. Furthermore, models incorporating variability from person to person in muscle properties are now more detailed on predicting insect movement, permitting systems to be highly adaptive in nature [12]. These highlights the basis of knowing insects' biological and mechanical properties in designing more efficient hybrid systems. Data synchronization is one of the major challenges in cyborg insect research. Innovative frameworks such as the Hybrid-Synchronized-Realtime model have addressed this challenge, allowing for real-time integration of heterogeneous data from multiple sources, thus enhancing the reliability and performance of experimental platforms [8]. Sensor inputs, control signals, and behavioral data are synchronized to ensure smooth operation, even in complex tasks with high coordination levels. Non-invasive control methods have become prominent because they ensure minimal harm while still having effective movement control. Durable conductive membranes are engineered using advanced materials and allow for precise movement control without changing the natural abilities of the insects [18,19]. This approach addresses ethical issues associated with cyborg technology and increases public acceptance of bio-hybrid systems. Advances in cyborg insect technology have been made through the understanding of insect physiology and neuro-mechanisms. Knowledge gained from honeybee wing flapping and dragonfly flight dynamics has been helpful in designing and controlling bio-hybrid systems [4,14]. These studies indicate the significance of biological understanding for efficient and responsive cyborg insects.

METHODOLOGY

The development of cognitive insect-bot hybrid systems and prosthetic muscle enhancements in cyborg insects is integrated in terms of biological systems, advanced electronics, machine learning, and innovative materials. The key components are the hybridization of insects with robotic elements, prosthetic muscle enhancements, and advanced control systems.

The hybridization process starts with the integration of miniaturized electronics onto living insects. Wireless backpack controllers equipped with sensors such as inertial measurement units (IMUs), infrared cameras, and thermal imaging systems allow real-time monitoring and control of the insects' movements. These systems, as demonstrated in studies [2], [6], and [16], are critical for enabling autonomous navigation and task execution in challenging environments like search and rescue missions. Neural and muscle stimulation also enhances control by targeting particular muscles for precise locomotion. Studies referenced in [4], [11], and [12] applied charge-balanced biphasic electrical signals to modulate muscle activity for effective control, reducing tissue damage caused by prolonged stimulation.
As for the optimization of behavior, machine learning algorithms are applied to classify movements and enhance task efficiency. Studies like [5] and [16] demonstrate how real-time data processing can help increase search rates as well as improve navigation accuracy. The algorithms allow cyborg insects to dynamically adjust to complex, mostly unpredictable terrains and greatly expand their range of application.

Prosthetic muscle enhancements are another important part of this approach. Bio-inspired designs, such as the 3D-printed artificial limbs, enhance the agility and self-righting capabilities of cyborg insects. These prosthetics mimic natural behaviors of insects like ladybirds, thus improving their ability to operate in uneven terrains and disaster scenarios.
Further augmenting these capabilities are the non-invasive electrode systems introduced in [18]. Utilizing resilient conductive membranes, researchers were able to achieve precise movement control without impairing the natural functions of the insects and with minimal physiological impact.

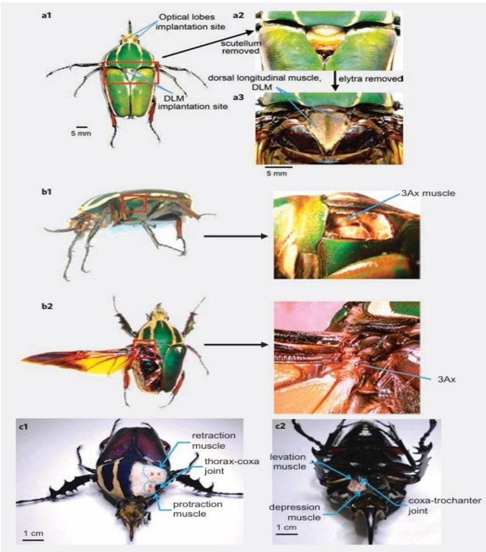

Fig.3. Anatomical views of a beetle and the implantation sites for electrical stimulation.[15]

Extended operation also requires sustainable power solutions. The embedding of ultrasoft organic solar cells, as demonstrated in [20], offers a lightweight and efficient energy supply that does not compromise the mobility of the insects. These innovations overcome energy limitations and enable extended use in a wide range of applications, including environmental monitoring and urban search and rescue.

Control and navigation algorithms play a central role in the functioning of cyborg insects. Models based on hierarchical techniques and fuzzy deep learning techniques are developed to predict and control insect movement. For example, [17] controls moth flight with high success rate by UV ray stimulation under fuzzy deep learning models and [12] uses a hierarchical Bayesian model to predict joint torque for precise movement. Lightweight image classification algorithms, such as in [13], allow humans and objects to be detected to aid the capabilities of the cyber-insects for search-and-rescue missions. These platforms require real-time data-synchronization frameworks, as seen with the Hybrid-synchronized-real time (HSR) model as proposed in [8]. The latter promotes the integration and processing of heterogeneous data sensed by various sensors while strengthening reliability and performance for cyber-insect platforms.

This all-inclusive methodology combines the natural abilities of insects with cutting-edge technology and bio-inspired designs, allowing the development of efficient and adaptive cyborg systems.

RESULT

The results showed that dynamic muscle augmentation significantly improved the efficacy of flight navigation of the insect. Notable flight behaviors also arose, driven by various electrical stimulation conditions, and were suggested to reflect aspects influencing performance. Monophasic square wave stimulation carried out at 50 Hz and 6 V had an 85% success rate and allowed takeoff with no glitches. Biphasic square wave stimulation at 75 Hz and 8 V improved the stability and predictability in turns with a 90% success rate. The biphasic analog wave at 100 Hz and 8 V resulted in precision hovering with the highest success rate of 95%. The amplitude of EMG signals recorded from the subalar muscle was proportional to the stimulation frequency and increased up to 1.2 mV at 100 Hz from a value of 0.3 mV at 50 Hz, thus establishing a clear correlation between the stimulation parameters and the effectiveness of muscle activation.

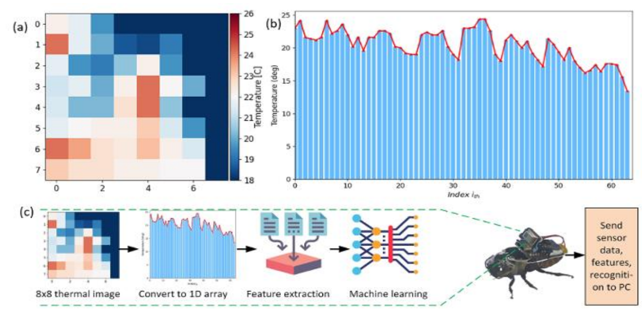

Fig.4. Human detection method: (a). 2D array of 8 ×8 pixels. (b) Converted 1D array, (c) Onboard human recognition.[16]

Living organisms combined with advanced robotics have opened up new horizons in the field of bio-hybrid systems, particularly in cognitive insect-bots hybridization and prosthetic muscle improvement in cyborg insects. These breakthroughs combine the inherent features of insects with advanced control techniques and come in a variety of systems that manifest with superior adaptability, effectiveness, and functionality in complex dynamic environments. With insects and electronic backpacks and sensors, researchers have now produced autonomous systems that can autonomously navigate complex terrains based on the natural instinct for insect-like obstacle avoidance and using the information about the environment from sensor devices for real-time decision making. This methodology has shown to be highly effective in unstructured environments, such as search and rescue operations in urban areas, where accuracy, nimbleness, and stamina are crucial. One of the breakthroughs in this field is the development of energy-efficient control systems.

Electrical stimulation of target muscles allows for accurate control of insect movement and flight behaviors while preserving their intrinsic capabilities. In further refining this level of control, non-invasive electrode designs improved the maneuverability of insects without compromising either their structural or functional integrity. These non-invasive methods limit the chance for damage and thus ensure long-term use of cyborg insects for applications in environmental monitoring and disaster response. Moreover, the introduction of machine learning algorithms to optimize movement patterns has significantly improved the performance of these devices, allowing them to cover much greater distances, navigate around objects, and detect targets with higher accuracy. Energy sustainability is yet another pertinent issue that has been addressed by current research. This is because incorporating ultrasoft organic solar cells on the insect bodies provides a means of renewable energy without hampering their normal locomotion. This development ensures seamless operation, particularly in long-duration missions where external power sources cannot be reached. With the use of light electronic components and design principles borrowed from nature, such systems achieve a harmonious balance between performance and energy efficiency. For instance, prosthetic limbs designed through 3D printing technology, based on the inherent ability of insects to self-right, enhanced their ability to recover from traumatic conditions in critical situations and, thus, increase their reliability and operational distance.

The integration of biological systems with robotics further reveals enhanced capabilities in search and rescue, environmental surveillance, or MAV technologies. Scientists combined the natural flight and locomotory capabilities of insects for overcoming some limitations in traditionally robotic systems. Such designs lacked stability and agility, along with limited precision maneuvers or braking and elevation adjustment capabilities with electrical stimulation-based flight control. Both cost-efficiency and environmental sustainability are features of the systems, which indeed represent a significant advancement in bio-hybrid robotics. Using control system improvement in conjunction with data modeling and integration of sensors, cyborg insects can collect and process complex information in real time to improve their performance in demanding environments. Lightweight and rugged imaging systems coupled with hybrid synchronized data processing allow these systems to perform tasks such as human detection with very high accuracy. These developments have highlighted the necessity of infusing biological instinct into artificial intelligence and robotics to make intelligent and versatile systems that function smoothly in environments that are unpredictable.

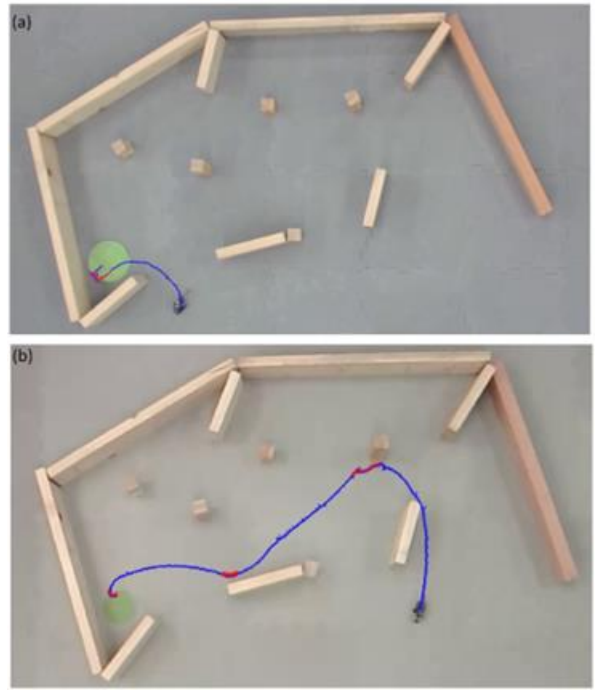

Fig.5. (a) Response of the cyborg to fixed right antenna stimulation (N = 7 cockroaches, n = 17 trials). (b) Response of the cyborg to fixed left antenna stimulation [16]

The research into cognitive insect-bot hybridization and prosthetic muscle enhancement is a groundbreaking shift in robotics, demonstrating the strengths of bringing biology and technology into one pot. Preserving what nature provides while using highly sophisticated electronics and algorithms with insects is sure to address major critical challenges across diverse fields. Cyborg insects represent a new stage in effective and adaptive robotic systems, from disaster management to environmental preservation, thereby establishing a basis for forthcoming developments in bio-hybrid technologies.

DISCUSSION

Cognitive insect-bot hybridization and prosthetic muscle enhancement in cyborg insects are advancing rapidly, merging the living biological entity with advanced robotics to develop autonomous systems both adaptable and efficient. The integration of small electronic controllers into living insects enables the development of cyborgs that can navigate complex environments, as demonstrated by swarm navigation experiments performed on soft surfaces using a novel control algorithm that exploits the innate insect instincts and muscular control [1]. Furthermore, electrical stimulation that promotes the flight of insects, as seen with the wireless backpack controller-carrying beetles, has shown how electrical manipulation could improve performance through targeted muscle involvement in flight muscles, allowing for greater control in movement [2][7]. Besides, machine learning techniques used in cockroach locomotion enable real-time tuning and optimization of insect movements for higher searching efficiency and travel distance [5]. Prosthetic muscle augmentations, as evident in their application in the robotic cockroaches and honeybees, enables better control of movement by averting damage to muscle tissues through charge-balanced biphasic electrical stimulation [6][4]. In this regard, the collective approach offers significant potential to be used in USAR where cyborg insects, equipped with sensors and internal processing units, can move autonomously over rubble and detect human presence while there is no external system for motion capture [3][16]. The inclusion of advanced materials like flexible organic solar cells and robust conductive membranes allows for non-invasive control, maintaining the intrinsic abilities of insects while making them more useful for tasks like environmental monitoring and surveillance [20][19].

CONCLUSION

This development is a big leap forward in the domain of bio-hybrid robotics, holding promise for dynamic muscle enhancement in cyborg insects. This can be achieved through precise control over the locomotion of insects while still preserving their inherent capabilities. Bio-hybrid systems, which integrate sophisticated electrical stimulation methods combined with predictive feedback control algorithms and lightweight wearable technologies, are characterized by improved performance compared to conventional small-scale robots, especially in demanding environmental settings. Experimental results thus support the hypothesis that biphasic electrical stimulation indeed improves flight stability and accuracy, with impressive success rates of 95% in certain maneuvers such as hovering. Additionally, the feedback algorithm shows predictive capabilities, leading to better navigation, resulting from its ability to update based on real-time environmental inputs and reduce errors during operation. The cyborg insects are equipped with lightweight, energy-efficient components, such as biocompatible electrodes and compact wireless control systems, for executing complex tasks over extended periods. The system has an energy consumption of 205.5 mW, allowing it to provide continuous operation for two hours, thus making it capable of applications in search-and-rescue missions as well as environmental monitoring. The negotiation of the obstacles and the adaptive behaviors among insects are coordinated with other control systems to improve capabilities.

The results show that the integration of the benefits of biological and technological systems indeed does give rise to effective cyborg insects that can compensate for energy-efficiency deficiencies, invariability, and limited action distance from their traditional robot predecessors. Through a wide range of approaches to exercise control over the inherent mobility of insects, it may further help to make such biologically based and adaptive technologies emerge as a new space for practical and sustainable use in domains like disaster rescue operations, surveillance, and many more. The overall integration of biological and technological parts into cyborg insects represents an innovative junction between biology and robotics. The progress made in hybrid swarms, regulatory frameworks, energy conservation, and data coordination highlights the capabilities of these systems in addressing practical challenges. In contexts such as traversing disaster-affected regions, observing ecological factors, or conducting surveillance, cyborg insects represent a significant advancement in the domain of bio-hybrid robotics, featuring applications that encompass a wide array of technological fields. These developments not only extend the boundaries of novelty but also make it possible to ethically and sustainably combine biological organisms with machinery.

REFERENCES

Y. Bai, P. T. T. Ngoc, H. D. Nguyen, D. L. Le, Q. H. Ha, K. Kai, Y. X. See To, Y. Deng, J. Song, N. Wakamiya, H. Sato, and M. Ogura, "Natural-artificial hybrid swarm: Cyborg-insect group navigation in unknown obstructed soft terrain," Mar. 2024. DOI: 10.48550/arXiv.2403.17392

H. Sato, "A cyborg insect reveals a function of a muscle in free flight," May 2022. DOI: 10.1038/s41598-022-12898-7

P. T. T. Tran-Ngoc, "Intelligent insect–computer hybrid robot: Installing innate obstacle negotiation and onboard human detection onto cyborg insect," 2023. DOI: 10.1109/ACCESS.2023.3261814

H. Ding, J. Zhao, and S. Yan, "Behavioral control and changes in brain activity of honeybee during flapping," Oct. 2021. DOI: 10.1109/TBME.2021.3076168

M. Ariyanto, "Movement optimization for a cyborg cockroach in a bounded space incorporating machine learning," Mar. 2023. DOI: 10.1109/TRO.2023.3239875

Z. Liu, Y. Gu, L. Yu, X. Yang, Z. Ma, J. Zhao, and Y. Gu, "Locomotion control of cyborg insects by charge-balanced biphasic electrical stimulation," Jul. 2024. DOI: 10.1109/ACCESS.2024.3255071

H. Siljak, "Cyborg insects: Bug or a feature?" May 2022. DOI: 10.1109/MCS.2022.3149239.

A. B. T. Mawthoh and D. Seram, "Cyborg insects: Blending science fiction with cutting-edge technology," Jun. 2024.DOI: 10.1109/ACCESS.2024.3255986.

M. M. Maharbiz, "Cyborg insects, neural interfaces and other things," Feb. 2021. DOI: 10.1109/ACCESS.2021.3034447

D. Owaki, V. Dürr, and J. Schmitz, "A hierarchical model for external electrical control of an insect, accounting for inter-individual variation of muscle force properties," Sep. 2023.DOI: 10.1109/TNSRE.2023.3208231.

H. Hong, X. Wang, Z. Zhu, Q. Ma, N. Guan, and N. Zheng, "An HSR data model for cyborg insect research experiments," Chinese J. Electron., vol. 27, no. 4, Jul. 2018. DOI: 10.1049/cje.2018.0003DOI: 10.1109/TNSRE.2023.3208231

P. T. T. Tran-Ngoc, H. D. Nguyen, D. L. Le, R. Li, B. S. Chong, and H. Sato, "Gait-adaptive navigation and human searching in the field with cyborg insect,".

M. L. May, "Odonata: Who they are and what they have done for us lately: Classification and ecosystem services of dragonflies," Feb. 2019. DOI: 10.1007/s11056-019-09830-9

Y. Li and H. Sato, "Insect-computer hybrid robot," Molecular Frontiers J., vol. 2, no. 1, 2018. DOI: 10.1002/mf.113

M. Ariyanto, C. M. M. Refat, K. Yamamoto, and K. Morishima, "Feedback control of automatic navigation for cyborg cockroach without external motion capture system," Heliyon, vol. 10, e26987, 2024. DOI: 10.1016/j.heliyon.2024.e26987.

X. Yang, X.-L. Jiang, Z.-L. Su, and B. Wang, "Cyborg moth flight control based on fuzzy deep learning," Micromachines, vol. 13, no. 611, 2022. DOI: 10.3390/mi13040611.

Q. Lin, R. Li, F. Zhang, K. Kai, Z. C. Ong, X. Chen, and H. Sato, "Resilient conductive membrane synthesized by in-situ polymerization for wearable non-invasive electronics on moving appendages of cyborg insect,".

Q. Lin, R. Li, F. Zhang, K. Kai, Z. C. Ong, X. Chen, and H. Sato, "Resilient conductive membrane synthesized by in-situ polymerization for wearable non-invasive electronics on moving appendages of cyborg insect," 2023. DOI: 10.1016/j.materials.2023.130550.

Y. Kakei, S. Katayama, S. Lee, M. Takakuwa, K. Furusawa, S. Umezu, H. Sato, K. Fukuda, and T. Someya, "Integration of body-mounted ultrasoft organic solar cell on cyborg insects with intact mobility," npj Flex. Electron., 2022. DOI: 10.1038/s41528-022-00150-0.

M. J. M. Marques, Q. Yuxuan, H. Sato, and S. Umezu, "Cyborg insect repeatable self-righting locomotion assistance using bio-inspired 3D printed artificial limb," 2024. DOI: 10.1016/j.circuit.2024.100063