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1- 2 Temmuz 2024

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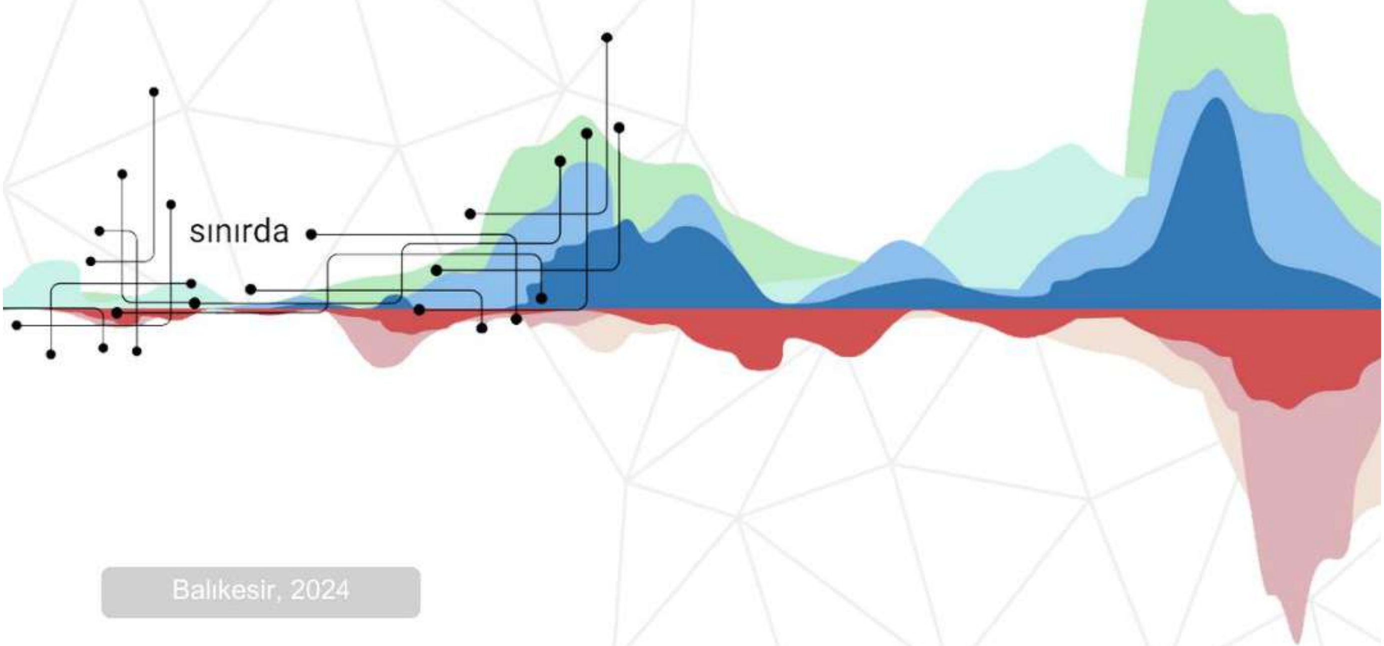

Balıkesir, 2024

XVIII. MİMARLIKTA SAYISAL TASARIM ULUSAL SEMPOZYUMU

1 – 2 TEMMUZ 2024 | BALIKESİR

MSTAS 2024 | SINIRDA

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BİLİM KURULU

Robotik Tasarım Yaklaşımlarında Sözel Olmayan İletişim Stratejileri: Myco-morphosis Örneği

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Özet

İnsanlar ve robotlar arasındaki etkileşim, tasarım ve inşaat araştırmalarında, özellikle kolektif üretim ve birlikte tasarım alanlarında, Yapay Zeka (AI - Artificial Intelligence) ve robotik alanlarındaki gelişmelerle ön plana çıkmıştır. Bu etkileşim, inşaat sürecindeki kalıp çalışmaları, üretim ve imalat gibi çeşitli yollarla araştırılmış ve insan yaratıcılığı ile robotik hassasiyeti senkronize edilerek işbirlikçi iş akışları oluşturmayı hedeflemiştir. Bu çalışmalarda beton, ahşap ve çelik gibi geleneksel endüstriyel yapı malzemeleri çevresel etkileri nedeniyle sorgulanmakta ve iklim krizi endişelerine yanıt olarak biyolojik bazlı malzemelere geçiş yapılmaktadır. Zamanla dönüşme ve evrimleşme yeteneklerine sahip biyolojik bazlı malzemeler, statik ve dayanıklı endüstriyel malzemelerin yerini alarak esnek tasarımlara olanak sağlamaktadır. Bu geçiş, tasarım ve inşaat süreçlerindeki işbirlikçi iş akışlarının ve özellikle robotik tasarım yöntemlerinin yeniden değerlendirilmesini gerektirir. Robotlarla etkili sözlü iletişim, bu bağlamda kritik bir öneme sahiptir ve KUKA Robotic Language (KRL) arayüzü gibi sistematik yöntemler ve Rhino, Grasshopper gibi görsel programlama arayüzleri aracılığıyla insan-robot etkileşiminin biyobazlı malzemeler odağında geliştirilme potansiyeline sahiptir. Bu araçlar, özellikle biyolojik bazlı malzemeler kullanıldığında sezgisel iletişimi kolaylaştırır ve işbirlikçi iş akışlarının yeniden değerlendirilmesini sağlayarak gerekli iyileştirmeleri sağlar.

Biyomateryallerden miselyum bazlı malzemeler, zamanla büyüme ve değişme yeteneklerine sahip olduğundan, farklı iletişim yöntemlerini gerektirir. Miselyum, mantarların vejetatif kısmı olup, tarımsal atıkları alt tabaka olarak kullanarak kademeli olarak sertleşen ve ağ yapısı oluşturarak büyüyen bir özellik gösterir. Bu büyüme özellikleri; renk, desen, doku ve morfoloji değişikliklerine dayalı sözel olmayan iletişim sistemlerinin kullanımını mümkün kılar, bu da robotik kolektif tasarım yöntemlerinde kritik bir rol oynar. Bilgisayarlı Görü (CV) teknikleri, görüntü sınıflandırma ve nesne tespiti gibi sözel olmayan iletişim sistemleri, gerçek zamanlı tepkileri mümkün kılarak insan-robot etkileşimlerini geliştirir. Bu teknolojiler, otomatik nesne tespiti ve robotik montaj gibi görevler için kritik önem taşır, ancak miselyum bazlı malzemelerin morfolojik durumu üzerine odaklanan az sayıda çalışma bulunmaktadır.

"Myco-morphosis" vaka çalışması insan, robot ve canlı biyolojik bazlı malzemeler arasındaki etkileşimleri kolaylaştıran sözel olmayan iletişim sistemlerini ve geri bildirime dayalı süreç odaklı metodolojiyi detaylandırmayı amaçlamaktadır. Miselyum bazlı tasarım için işbirlikçi bir çerçeve oluşturmayı, gerçek zamanlı etkileşimleri incelemeyi ve yaratıcı tasarım süreçleri ve kolektif iş akışı hakkındaki temel araştırma sorularını ele almayı hedeflemektedir. Çalışma, 5 aşamada sürdürülmüştür: (1) etkileşim aktörlerinin ve rollerinin tanımlanması, (2) modüler tasarım sürecinin tanımlanması, (3) laboratuvar deneylerinin ve veri toplama yöntemlerinin açıklanması, (4) CNN (Convolutional Neural Network) modelinin eğitimi ve sistem senkronizasyonu ve (5) sözel olmayan iletişimin ve insan-robot-biyomateryal işbirliğinin dijital simülasyonu. Bilgisayarlı Görü teknikleri, görsel programlama yazılımları ve robotik kollar kullanılarak, bu çalışma insan-robot-canlı miselyum etkileşimlerinin karmaşık etkileşimini araştırmayı ve doğa tabanlı tasarım metodolojilerine katkıda bulunmayı amaçlamaktadır. Myco-morphosis biyolojik bazlı malzemelerin kullanıldığı tasarım süreçlerinde yaratıcı çözümler sunmayı hedeflemektedir.

Anahtar Kelimeler: *Sözsüz iletişim, robotik tasarım yöntemleri, biyo-tabanlı materyaller, kolektif yaratım, ortak tasarım, bilgisayarlı görme.*

Non-Verbal Communication Strategies in Robotic Design Approaches: The Case of Myco-morphosis

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Abstract

The interaction between humans and robots has become a focal point in design and construction research, particularly in the realms of co-creation and co-design, driven by advancements in Artificial Intelligence (AI) and robotics. This interaction has been explored through various avenues such as formwork studies, creation, and fabrication within the construction process, aiming to synchronize human creativity with robotic precision to create collaborative workflows. Traditional industrial building materials like concrete, wood, and steel are being scrutinized for their environmental impact, prompting a shift towards bio-based materials in response to climate crisis concerns. Bio-based materials, characterized by their ability to transform and evolve over time, are replacing static and durable industrial materials, enabling flexible designs. This transition necessitates a reevaluation of collaborative workflows in design and construction processes, particularly in robotic design methods. Effective verbal communication with robots is crucial in this context, with systematic methods such as the KUKA Robotic Language Interface (KRL) and visual programming interfaces like Rhino and Grasshopper enhancing human-robot interaction with a focus on bio-based materials. These tools facilitate intuitive communication, especially when incorporating bio-based materials, and enable necessary improvements by reassessing collaborative workflows.

Mycelium-based materials, being a subset of biomaterials, require different communication methods due to their growth and change capabilities over time. Mycelium, the vegetative part of fungi, utilizes agricultural waste as substrates, gradually solidifying and forming a network structure as it grows. These growth characteristics allow the use of non-verbal communication systems based on changes in color, pattern, texture, and morphology, which play a critical role in robotic co-design methods. Computer Vision (CV) techniques, such as image classification and object detection, enhance human-robot interactions by enabling real-time responses. These technologies are vital for tasks such as automatic object detection and robotic assembly, yet few studies have focused on the morphological status of mycelium-based materials.

The "Myco-morphosis" case study aims to elaborate on the non-verbal communication systems and feedback based process-led methodology that facilitate interactions between humans, robots, and living bio-based materials specifically mycelium. It seeks to establish a collaborative framework for mycelium-based design, examine real-time interactions, and address fundamental research questions regarding creative design processes and collective workflows. The study is structured into five stages: (1) identification of interaction actors and their roles, (2) definition of modular design process , (3) description of laboratory experiments and data collection methods (4) training the CNN model and system synchronization and (5) simulating the non-verbal communication and human-robot-mycelium collaboration computationally. Utilizing CV techniques, visual programming software, and robotic arms, this study aims to investigate the complex interplay of human-robot-living mycelium interactions and contribute to nature-based design methodologies. Myco-morphosis aims to offer creative solutions in design processes involving bio-based materials.

Keywords: *Non-verbal communication, robotic design methods, bio-based materials, collective creation, co-design, computer vision.*

1. Introduction

The interaction between humans and robots has become a focal point in design and construction research, particularly in the realms of co-creation and co-design, driven by advancements in Artificial Intelligence (AI) and robotics. This change is primarily driven by developments in AI and robotics, significantly expanding the possibilities for integrating robotic systems into creative and practical applications. Recent studies highlight the importance of human-robot interaction at various stages of construction processes. Culver et al. (2016) and Yang et al. (2019) have examined this interaction through formwork studies, demonstrating that synchronizing robotic precision with human creativity can enhance construction efficiency. Similarly, Mitterberger et al. (2022) have investigated the role of robots in production processes, while Ercan Jenny et al. (2023) have explored integrated fabrication processes, underscoring the potential for collaboration between humans and robots.

Critical developments in sustainability and environmental impact have prompted a reevaluation of traditional industrial building materials such as concrete, wood, and steel. Although these materials are durable and widely used, their environmental footprints contribute to climate change and resource depletion. In response to these concerns, there is a growing interest in bio-based materials, which are derived from renewable sources and possess the ability to transform and evolve over time. Bio-based materials such as mycelium, the vegetative part of fungi, offer promising alternative behaviors due to their sustainable nature and unique properties. Mycelium can utilize agricultural waste as substrates, gradually solidifying and forming a network structure as it grows, making it a potential candidate for innovative construction applications (**Figure 1**).

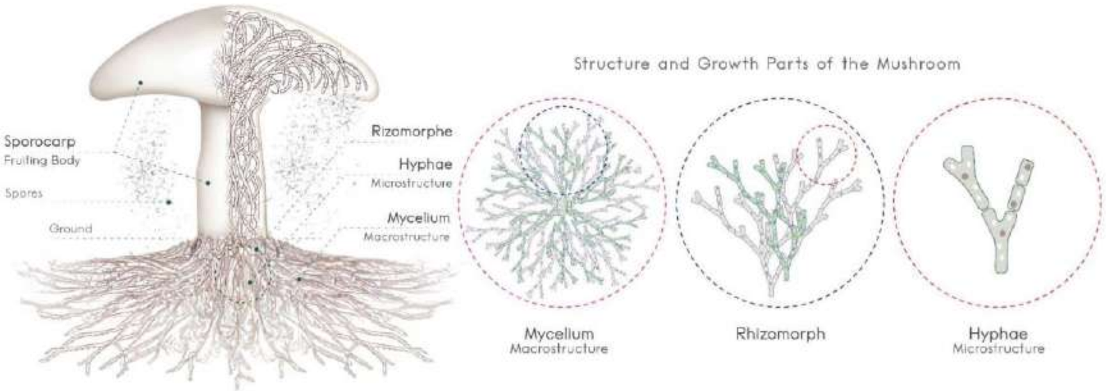

Figure 1. Structure and growth parts of the mushroom: mycelium (macrostructure), rhizomorphs, and hyphae (microstructure) (Source: authors).

Systematic methods such as the KUKA Robotic Language Interface (KRL) and visual programming interfaces like Rhino and Grasshopper establish verbal communication channels in human-robot interaction. However, the integration of bio-based materials into design, creation and construction processes introduces new challenges in these communication channels. Existing workflows and design methods developed for static materials are not suitable for living materials found in nature. This necessitates the development of new collaborative workflows and design approaches that can effectively integrate the dynamic nature of bio-based materials into the system. In this context, non-verbal communication between humans, robots, and bio-materials becomes critical.

Living biomaterials like mycelium, which have the ability to grow and change over time, present several challenges compared to traditional materials. Effective integration of these biomaterials into design and construction workflows requires the development of new communication methods and interactive collaboration techniques that facilitate the interaction between humans, robots, and bio-based materials. These methods must adequately manage the dynamic properties of these materials and adapt to their changes throughout the process.

The primary objective of this research is to explore and develop non-verbal communication systems that facilitate the interaction between humans, robots, and living biomaterials. This study addresses the Myco-morphosis case, which aims to establish a collaborative framework for mycelium-based design. The framework seeks to enhance process-oriented design and collaboration, building upon the work of Alima et al. (2022) on the dynamics of mycelium-based design. Unlike Alima et al.'s study, which uses a final design to observe material behavior and feedback, this research structures a process-led design problem to address interactions through non-verbal communication. By utilizing Computer Vision (CV) techniques, visual programming software, and robotic arms, this study aims to contribute to nature-based design methodologies by investigating the complex interplay of human-robot-living mycelium interactions..

2. Theoretical Background

2.1. Introduction to Human-Robot Interaction in Design and Construction

Culver et al. (2016) and Yang et al. (2019) provided significant insights into Human-Robot Interaction (HRI) through their studies on mold patterns, laying the foundational principles of this field. Mitterberger et al. (2022) expanded upon this research by focusing on the role of robots in production processes rather than design, emphasizing the increasing integration of robotic systems in construction and fabrication environments. Building on these advancements, Ercan Jenny et al. (2023) examined integrated fabrication processes, highlighting the potential for collaboration between humans and robots. Their research showed that the synergy between human creativity and the precision and repeatability of robotic systems can lead to more efficient and flexible construction processes. The integration of robotic precision with human creativity promises a transformative impact on the design and execution of construction and manufacturing processes.

2.2. Bio-based Materials and Mycelium

Bio-based materials, such as mycelium, offer sustainable alternatives that require a reevaluation of collaborative workflows in design and construction processes (Thomsen, 2021; Modanloo et al., 2021; Thomsen & Tamke, 2022). Mycelium has significant potential for transformative changes in the construction industry, being utilized in various architectural applications like bio-composites, building components, and scaffolds for biomineralized engineered living materials (Attias et al., 2020; Viles, 2024; Muiruri et al., 2023). These mycelium-based composites are renewable, biodegradable, and align with circular economy principles, utilizing waste products as substrates and promoting biodiversity (Bitting et al., 2022; Barta, 2024).

The use of mycelium in architecture supports sustainable development principles by offering eco-friendly and resilient building practices (Echavarri-Bravo et al., 2019; Muiruri et al., 2023). It enables the creation of modular interlocking systems, living structures, and components for 3D printing and robotic deposition, thereby expanding the applications of bio-based materials in architecture (Abdelhady et al., 2023; Diniz & Melendez, 2023; Ilgün & Schmickl, 2022). Combining digital technologies with biological processes allows for the development of bio-inspired architectural systems, integrating sustainability with advanced design principles (Chayaamor-Heil et al., 2023; Diniz & Melendez, 2023). The living and evolving nature of mycelium highlights the need for a new communication model to effectively integrate its dynamic properties.

2.3. Verbal Communication Models in Robotic Design

The integration of verbal communication models in robotic design is essential for improving human-robot interaction (HRI) in architecture. Effective communication between robots and users is critical for successful collaboration. Frijns et al. (2021) introduced the "AMODAL-HRI" model, a framework based on joint action theory, common robot architectures, and cognitive architectures, providing a comprehensive foundation for verbal communication strategies in HRI. Yablonina et al. (2021) emphasized the importance of architecturally embedded machines in adaptive spatial interactions, exploring innovative human-robot collaboration in spatial configuration tasks.

Banerjee & Moses (2010) contributed by enhancing modular robotic systems' communication through an immune system-inspired impact-response strategy, offering insights into robust communication architectures. Wei et al. (2008) proposed a middleware-based approach for flexible and scalable control architectures in modular robotic systems, focusing on component-based software architecture for reusability and interoperability. These studies collectively offer essential guidance for integrating verbal communication models into architectural robotic systems, ensuring effective and seamless human-robot collaboration.

2.4. Non-verbal Communication Potential with Computer Vision

The potential of Computer Vision (CV) technologies to enable real-time non-verbal communication in robotic design has been highlighted in various studies. Zhong (2024) explored the use of deep learning-based computer vision to enable robots to understand non-verbal human expressions, such as body language, in crowded public spaces. This research emphasizes that computer vision can enhance the effectiveness of robot interactions in dynamic and variable environments. Misaros et al. (2023) introduced an application that enhances human-robot communication by monitoring and interpreting gestures and facial expressions, further proving the impact of computer vision on non-verbal communication. Mazhar et al. (2018) presented a framework for real-time physical human-robot interaction using hand gestures, demonstrating how robots can be adaptive and responsive during physical interactions. Ritschel et al. (2019) focused on synthesizing intentional and emotional non-verbal sounds for social robots, highlighting the role of audio design in robot communication and interaction. This study shows that auditory cues are crucial in complementing visual cues to convey emotions and intentions effectively in robotic feedback mechanisms.

In addition to these technological advancements, the inclusion of living materials such as mycelium in design holds potential for further enhancing non-verbal communication models. Mycelium's ability to grow and respond to environmental stimuli by forming dynamic and interactive surfaces can convey information through its physical changes. This characteristic allows mycelium to be perceived by robots as a form of body and gesture language. Integrating such living materials into robotic design can enable robots to interact with their environments and users in more organic and intuitive ways, adding new dimensions to non-verbal communication.

3. Methodology

The Myco-morphosis case study focuses on non-verbal communication systems to thoroughly examine interactions between humans, robots, and biological materials. The research of Alima et al. (2022) on robotic production and nature-based design dynamics forms the foundation for creating a collaborative framework for mycelium-based design in this research. However, instead of using a final design to observe material behavior and feedback, Myco-morphosis structures a process-oriented collaborative design problem. This aims to study interactions through non-verbal communications. Using design-focused research methods, Myco-morphosis seeks to simulate the resolution of a process-led design problem, investigate real-time interactions, and address fundamental research questions about creative design processes and collective workflows (**Figure 2**).

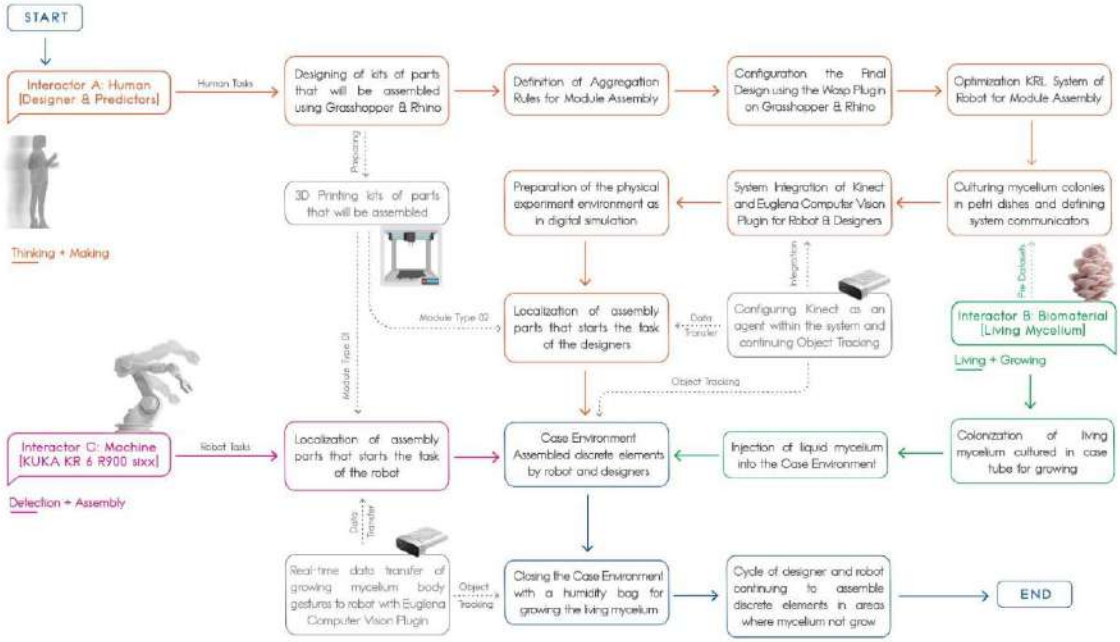

Figure 2. Process-led and practice-based methodology workflow diagram.

The Myco-morphosis study uses a collective and improvisational design approach to enable dynamic and adaptive interactions between humans, biological materials, and machines (**Figure 3**). The improvisational and collective design approach in this study includes dynamic communication and feedback mechanism, real-time monitoring and adaptation, collective design and integration. Humans and robots detect and respond to mycelium growth patterns and accordingly they adjust the assembly process through a dynamic communication and feedback mechanism. This communication and feedback emergence is enabled via real-time monitoring and adaptation where the Kinect monitors the mycelium in real-time and feeds the robot movements for real-time decision-making. Consequently, humans and robots develop strategies based on mycelium growth, which robots implement, allowing the biological material to shape the structure organically.

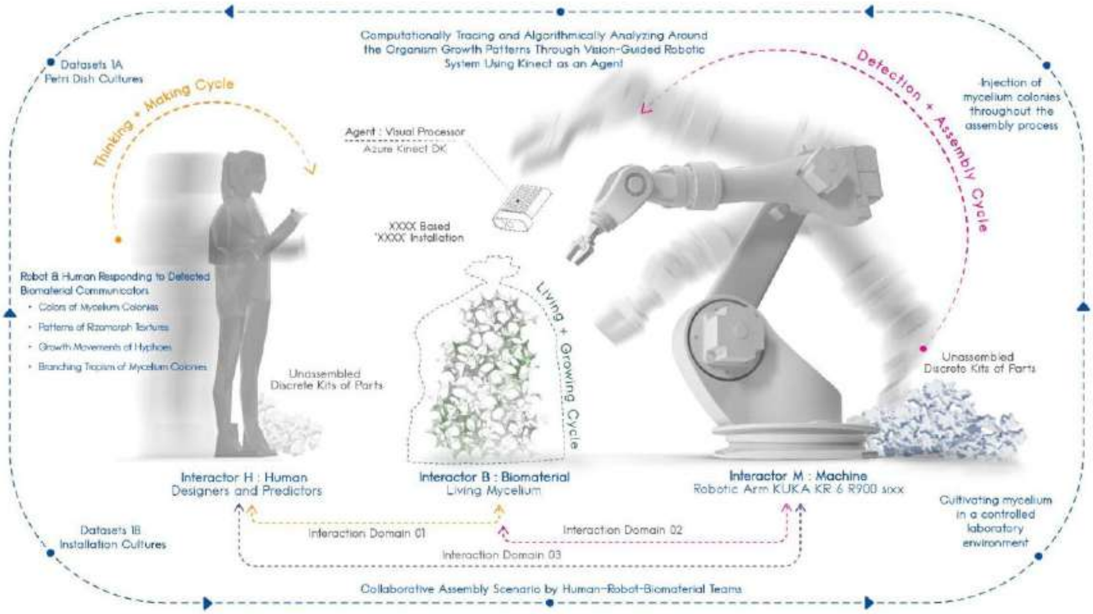

Figure 3. Improvisational and collective design approach: collaborative assembly scenario between interactors and tasks cycles.

The study is structured into five stages: (1) identification of interaction actors and their roles, (2) definition of modular design process , (3) description of laboratory experiments and data collection methods (4) training the CNN model and system synchronization and (5) simulating the non-verbal communication and human-robot-mycelium collaboration computationally.

3.1. Interaction Actors and Roles

Myco-morphosis which involves Human-Robot-Biomaterial collaboration, the identification of different actors and their specific tasks is crucial for the system's efficiency and the successful completion of the case. Turn-taking task distribution with feedback mechanisms comprises multi-actor interactions including human operators, digital design models, visual processors, robotic arms, and biomaterials. Each actor assumes specific roles throughout the processes of thinking, sensing, application, and assembly.

Humans, who are the initial actors, are labeled as *Interactor H* in this study. Humans identify and gather the unassembled discrete modules, which prepares them for subsequent tasks. They then evaluate the visual properties of the modules, including observing the growth and adhesion processes of the biomaterial. Based on the results of this visual analysis, they make strategic plans and design decisions regarding the module assembly. . After the analysis and planning phase, they assemble the modules at designated points, maintaining the system's integrity and thus becoming key actors in the design process.

Robots which are named as *Interactor R,* analyze visual data to identify and classify the modules, perceiving the growth, morphology, and adhesion of biomaterials on the modules. They then merge and combine information from the KUKA|prc command sequence to determine the position of the modules. Based on the integrated data, robots apply the predetermined rule system and execute the LIN (Linear Movement) commands specified in the sequence. In the picking task, robots grasp and move the modules. They perform the stabilization task to ensure that the modules are placed securely and stably. Finally, in the placement and release task, robots position and release the modules at the correct location, thus completing the design and assembly.

Biomaterial as the third actor named as *Interactor B*. The growth routine ensures the mycelium grows in a controlled environment, adhering to the modules and taking the desired form, guiding the organic shaping of the structure.

3.2. Modular Design Process

This study advances collaborative mycelium-based design by simulating digital design processes. It involves digitally designing modules for different tasks, ensuring structural integrity and assembly flexibility.The reason for selecting modular design is to enable the robot to facilitate pick and place operations and to more easily orient organic structures, thereby allowing for creative solutions. The design process supports both robotic and manual assembly, allowing the modules to adapt to various scenarios. **(Figure 4)** Connection points enhance structural consistency and simplify assembly, while collection rules ensure a holistic and flexible system operation.

The modules are designed for multiple assembly in a digital environment, promoting compatibility, balance, and stability. Their organic forms and fluid surfaces increase the growth area for mycelium, supporting optimal growth conditions and adherence. Three different digital assembly scenarios (**Figure 4**) have been defined for the case study: Robots assemble Module A, which can self-replicate at eight points through an automated digital process. Robots follow a predetermined program for acquiring, positioning, and assembling the modules. Humans assemble Module B, which can self-replicate at four points through a manual digital process. This scenario leverages human creativity and decision-making, offering flexibility for complex structural requirements. A hybrid approach where robots and humans collaboratively assemble Modules A and B; robots handle repetitive tasks, while humans manage flexible and complex tasks, enabling effective collaboration and innovative design solutions.

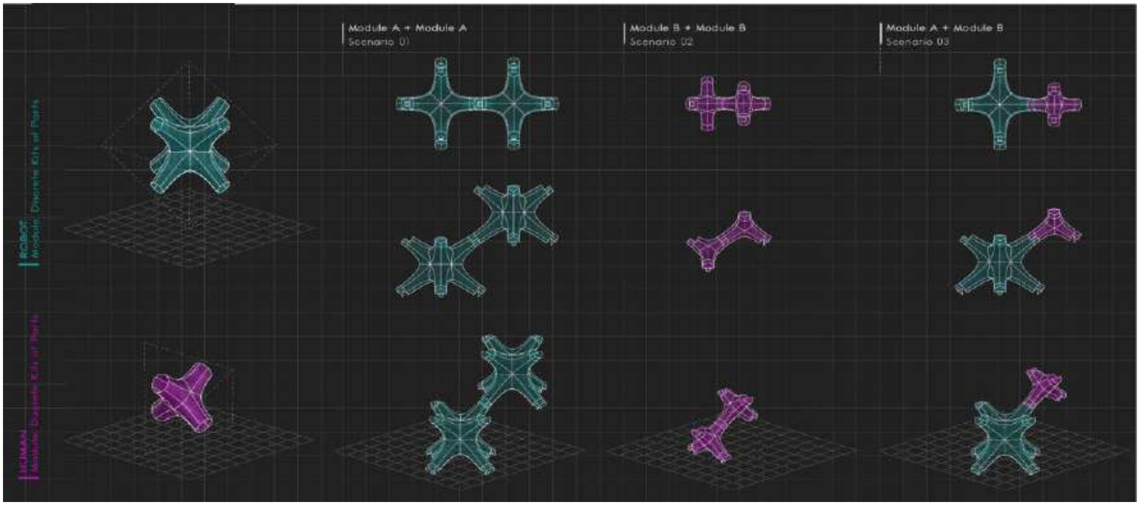

Figure 4. assembly scenarios of modules included tasks of robots and humans.

Rules were established to ensure structural integrity and functionality, enabling proper module assembly and a structured hierarchy. The design supports effective mycelium positioning and adherence, increasing its surface area for optimal growth. The system and scenarios allows flexible use of modules and adapts to both robotic and manual assembly, facilitating complex and dynamic digital design processes.

3.3. Laboratory Experiments and Data Collection Methods

Two laboratory experiments were conducted. In the first, mycelium from Pleurotus citrinopileatus and Pleurotus djamor was inoculated into 50 Petri dishes and monitored under various environmental conditions (**Figure 5**). Parameters such as growth, colony diameter, color changes, and contamination were recorded to create a dataset for a computer vision model.

Figure 5. Inoculation of Pleurotus Citrinopileatus mycelium into an SDA Petri dish under controlled conditions (A), initiation of the mycelium cultivation process, and mycelium cultures in petri dishes (B).

First experiment showed that high humidity and low light accelerated mycelium growth. Pleurotus citrinopileatus grew fastest in high humidity and darkness, with colony diameters up to 35 mm, exhibiting a filamentous, dense structure with wavy edges. Pleurotus djamor performed best in medium humidity and low light, with colony diameters of 28-30 mm, featuring a cottony, dense structure with smooth edges.

Figure 6. Inoculation of liquid mycelium into a module designed under controlled conditions, initiation of the mycelium cultivation process, and mycelium cultures on designed modules.

In the second experiment, mycelium was injected onto 3D-printed models using a bamboo-based filament (**Figure 6**). The experiment aimed to study mycelium growth in confined spaces and under various environmental conditions, using the same mycelium species (**Figure 7**). Parameters such as growth rate, colony diameter, color change, and structural morphology were recorded. The shape and size of the modules, along with the material, impacted mycelium adhesion and spread. This data formed the secondary dataset for training a CNN model.

Figure 7. Living mycelium traces and details observed on the modules after inoculation.

Results indicated that high humidity and low light conditions promoted faster, denser mycelium growth with filamentous structures and wavy edges. In low humidity and high light, growth slowed, colonies turned dark gray, and structures became sparse. Module size and shape influenced growth direction and speed, with larger colonies in wide, deep areas and limited growth in narrow, shallow spaces. These findings highlight the mycelium's sensitivity to environmental conditions and its behaviors in real-world scenarios.

3.4. Training the CNN Model and System Synchronization

The data from these experiments show how mycelium characteristics, such as color, rhizomorph texture patterns, hyphal growth movements, and branching tropism, respond to environmental conditions. These changes are interpreted as biological responses to environmental stress.

Figure 8. Living mycelium traces and details observed on the modules after inoculation.

Rhizomorph texture patterns are a significant parameter during mycelium growth. Growth movements and branching tropism varied with environmental conditions. Under high humidity and low light, the mycelium exhibited a filamentous, dense structure with wavy and pointed edges. Conversely, under low humidity and high light, growth slowed, and colonies became sparse and filamentous. This indicates mycelium sensitivity to environmental signals, expressed through biological and morphological changes.

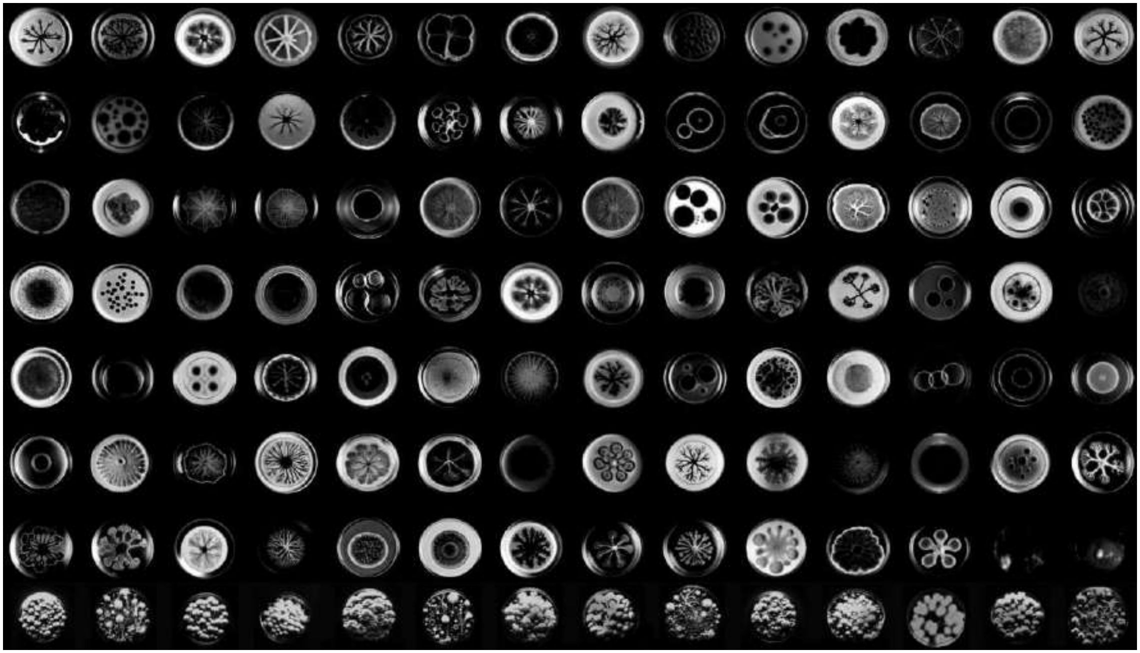

Figure 9. Depth Map of Rhizomorph Texture Patterns- Visual representation of mycelium growth, showing dense structures in high humidity/low light and sparse growth in low humidity/high light.

Physical data were used to create depth maps with the Azure Kinect tool, capturing both photographic images and depth maps. (**Figure 9**) Two datasets were created: (Dataset 1A) from Petri dish mycelium cultivation experiments, revealing growth characteristics under different conditions, and (Dataset 1B) from designed module growth experiments, showing mycelium growth in confined spaces and its response to various environmental conditions and microorganisms (**Figure 8**).

These primary and secondary datasets trained a Convolutional Neural Network (CNN) model. Image processing techniques like rotation, translation, and brightness adjustments augmented the datasets. The dataset was split into 80% for training and 20% for validation. Model training used TensorFlow and Keras libraries, building the CNN with the Sequential API and various layers. Regularization techniques like Dropout and BatchNormalization prevented overfitting, and EarlyStopping stopped training if validation loss didn't improve for 10 epochs (**Figure 11**).

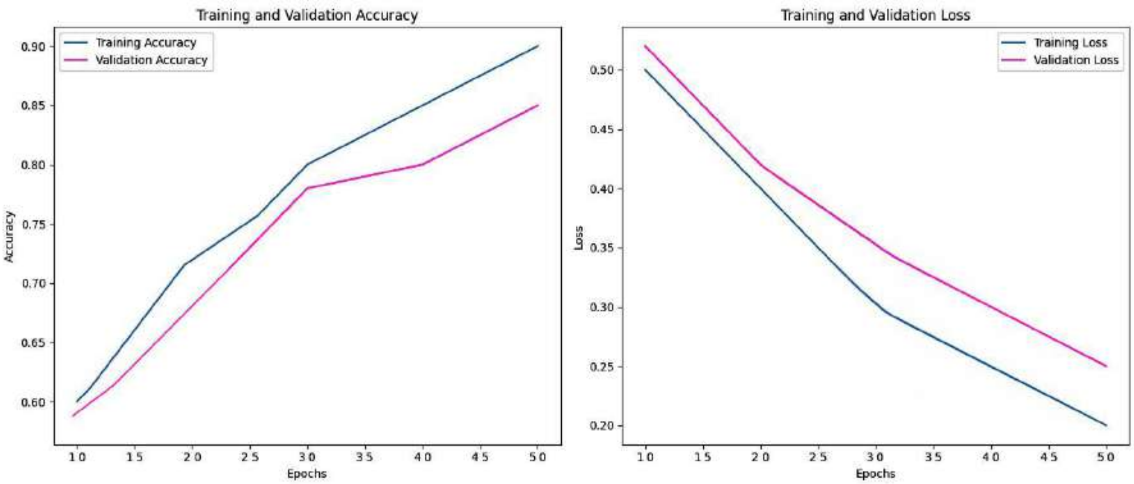

Figure 10. Visualization of CNN Model Training Results - This graph depicts the training and validation accuracy (A) and loss over epochs (B), illustrating the model's performance and convergence throughout the training process.

During training, the model's performance was evaluated by monitoring training and validation accuracy and loss values. An increase in training accuracy and a decrease in loss values indicated good performance. However, early stabilization of validation accuracy and low validation loss suggested overfitting. To address this, more aggressive data augmentation, increased model complexity, and extended training duration were applied. These improvements led to better performance on both training and validation datasets. (**Figure 10**) The trained CNN model achieved high accuracy in classifying mycelium growth.

The trained model was integrated with the Script Component in Rhino Grasshopper, enabling the KUKA robot to identify mycelium growth areas based on color and texture. The model is linked to a Pick & Place routine in KUKA|prc, where it analyzes modules for mycelium growth, classifying them as "Mycelium Growth Present" or "Mycelium Growth Absent" (**Figure 12**). These classifications are communicated to the robot, which then skips placing in areas with mycelium and completes placing in areas without mycelium using "LIN" (Linear Movement) commands to systematically move between specified points.

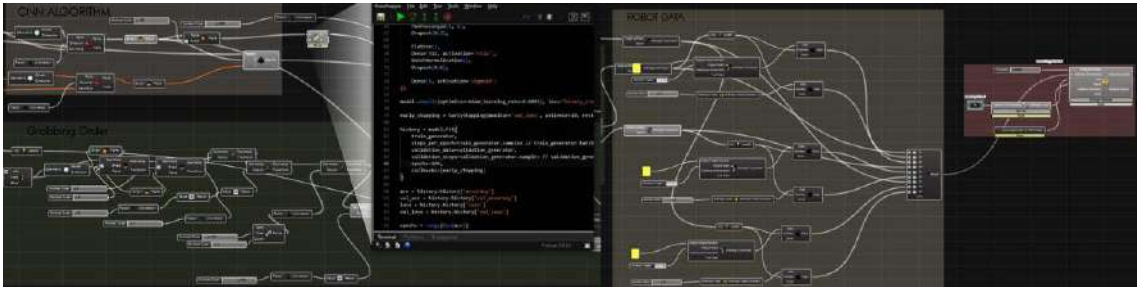

Figure 11. Integration of CNN Model with KUKA|prc - The model detects mycelium growth and guides the KUKA robot's Pick & Place routine, selectively avoiding areas with mycelium.

This setup enables the robot to obviously identify and respond to the mycelium growth surface, optimizing its actions based on the model's analysis. The growth areas and characteristics of mycelium serve as a "body language and gestures" for guiding the robot's movements and tasks. This approach enhances the use of biological data in robotic applications, improving the understanding of mycelium's intuitive interactions.

3.5. Computational Simulation: Testing Non-verbal Communication Procedure

This study conducted a computer simulation focusing on the collaboration between robots and humans for module placement and mycelium injection using KUKA|prc and Grasshopper. Initially, the robot correctly positioned five modules, with two placed independently and two interlocked. Simultaneously, seven modules planned for human placement were integrated, with three attached to robot-placed modules, three independent, and two interlocked.

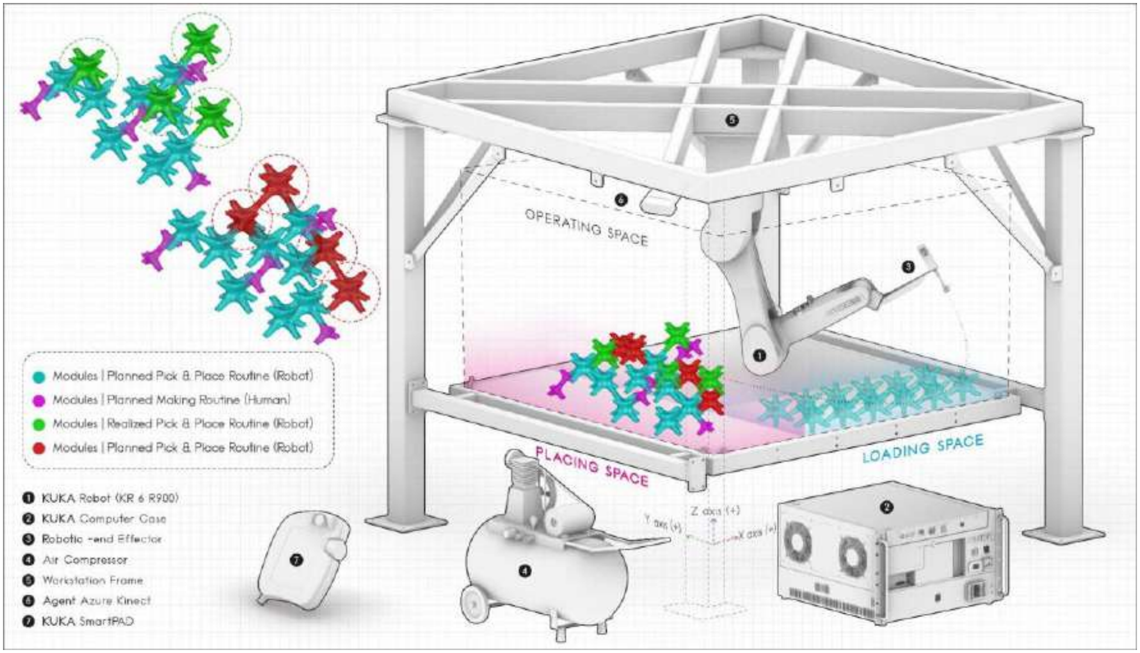

Figure 13. Mycelium Detection Simulation Based on Color and Texture as Morphology - The robot identifies mycelium growth using color analysis, halting assembly in detected areas.

To simulate mycelium injection, Kinect depth map data of mycelium colonies were overlaid on the structure, and the robot observed these shadowed spots for 10 seconds. The robot scanned for mycelium traces and classified modules as either having mycelium growth (True-1) or not (False-0). For modules without mycelium, the robot continued its Pick and Place routine. (**Figure 13**) For those with mycelium, the robot halted assembly. This process was repeated using both color and texture analysis. The robot successfully distinguished mycelium growth and responded in real-time, demonstrating its capability to detect and appropriately react to mycelium based on both color and texture features.

4. Result and Conclusion

The study successfully demonstrated the integration of non-verbal communication systems in robotic design through computational simulations and laboratory experiments regarding the Myco-morphosis case. Myco-morphosis study demonstrates the potential of integrating bio-based materials, such as mycelium, into robotic design and construction processes, highlighting the applicability and effectiveness of non-verbal communication systems. The combination of computer vision techniques and real-time data processing has enabled the KUKA robot to dynamically interact with mycelium, responding to growth patterns and environmental stimuli. The findings indicate that environmental conditions significantly influence mycelium growth and that these growth patterns can be effectively monitored and interpreted using advanced computer vision technologies. The successful integration of the trained CNN (Convolutional Neural Network) model with the KUKA robot's operational system underscores the importance of developing intuitive and non-verbal communication frameworks for human-robot-biomaterial interactions. These frameworks allow the robot to interpret living material growth patterns, colors and morphological changes as a form of body language and gesture, optimizing its movements and operational tasks.

This research contributes to nature-based design methodologies, proving that innovative communication models can be developed to accommodate the dynamic properties of living, evolving bio-materials. By leveraging the compatible properties of mycelium and advanced robotic systems, the study paves the way for more sustainable and adaptable construction practices. The use of non-verbal communication systems enables robots to interact with bio-materials in a more organic and intuitive manner, fostering a natural, efficient, and collaborative working environment, and facilitating collective designs and creations. Within the scope of this study and results of simulation, the non-verbal communication strategies can be listed as follows:

Table 1. The non-verbal communication strategies according to the analysis of Myco-morphosis case.

Strategies	Description
Integration of Computer Vision Technology	Utilize advanced computer vision technologies to detect and monitor the growth patterns, color, and morphological changes of living bio-materials.
Real-Time Data Processing	Employ real-time data processing techniques to track the growth rate and direction of bio-materials and provide dynamic feedback based on this data.
Use of Machine Learning Models	Implement machine learning and deep learning models (e.g., Convolutional Neural Networks) to classify growth patterns of bio-materials and integrate these classifications into robotic systems.
Development of Intuitive Communication Frameworks	Create intuitive and non-verbal communication frameworks for human-robot-biomaterial interactions, establishing protocols that allow robots to interpret the physical changes of bio-materials.
Response Mechanisms	Develop mechanisms that enable robots to dynamically respond to the growth patterns, colors, and morphological changes of bio-materials.
Optimization of Human-Robot-Biomaterial Interactions	Develop new communication models to optimize interactions between humans, robots, and bio-materials, using biological data to create more natural and efficient working environments.
Dynamic Feedback Mechanisms	Provide real-time feedback to robotic systems by monitoring and analyzing the reactions of living bio-materials.
Adaptive Algorithms and Learning Systems	Develop continuously learning algorithms that enable robotic systems to adaptively respond to the growth and changes of bio-materials, predicting their development and adjusting accordingly.
Bio-Material Interactive Surface Design	Design special surfaces and structures that facilitate interaction between robots and bio-materials, supporting natural movements and growth of the materials while enabling robots to detect and respond to these changes.
Visual and Tactile Feedback Systems	Monitor and evaluate the interactions of robots with bio-materials through visual and tactile feedback systems, providing more precise and accurate interactions by conveying the physical responses and changes of the bio-materials to the robots.
Bio-Material Based Communication Protocols	Develop specific communication protocols to standardize the interaction between living bio-materials and robots, converting the physical and chemical signals of bio-materials into data formats that robots can understand.

Future research should focus on further improving these non-verbal communication models and exploring their applicability in broader architectural and construction contexts. Integrating robotic systems with bio-materials has the potential to create revolutionary changes in the construction and design fields.

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