Mobile Module in Reconfigurable Intelligent Space: Applications and a Review of Developed Versions

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***Abstract*—Due to the immobility of devices in conventional intelligent spaces, the quality and quantity of their applications (i.e., services) are thus restricted. To provide better and more applications, the devices in the spaces must be able to move autonomously to ideal positions. To solve this issue, the concepts of reconfigurable intelligent space (R+iSpace) and mobile modules (MoMos) have been introduced. Each device in the R+iSpace is carried by one or more MoMos that can freely move on the ceiling and walls. Consequently, the R+iSpace has evolved into a user-centered intelligent space, where devices can move to the user to provide services instead of the user having to move to where the devices are. In this work, several promising applications are introduced as open research challenges for the R+iSpace and the MoMo. In fact, various wall-climbing robots have been developed, however, their speed and carrying capacity are insufficient for adoption for the MoMo and the R+iSpace. Therefore, the development of MoMo requires the creation of entirely new designs and mechanisms. In addition to introducing promising applications, this work provides an overview of all versions of the MoMo that have been developed to gradually make it deployable in a realistic R+iSpace.**

***Keywords*—Climbing Robot; intelligent space; iSpace; mobile module; MoMo; reconfigurable intelligent space; R+iSpace; smart home; ubiquitous environment**

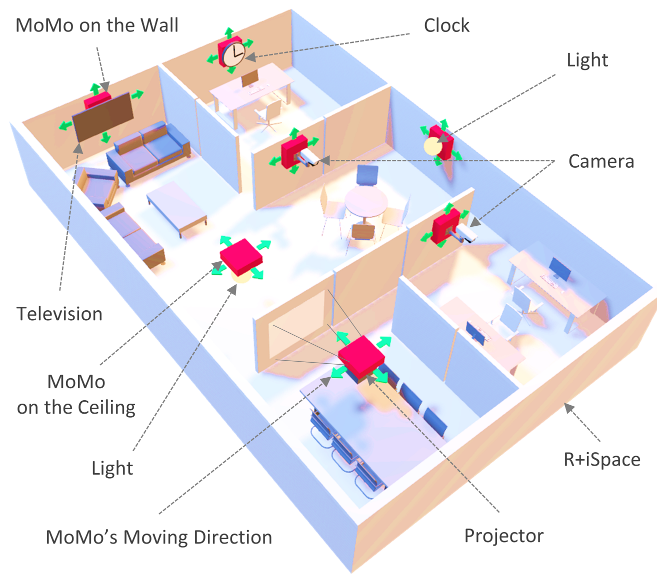


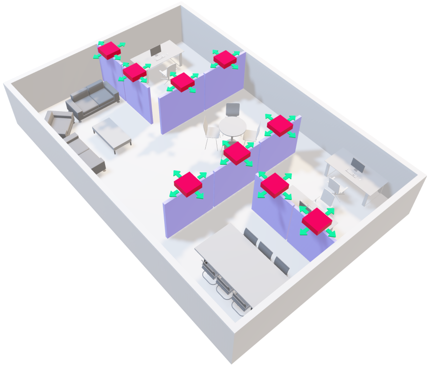
Fig. 1. A conceptual reconfigurable intelligent space with mobile modules (MoMos).

I. Introduction

Recently, terms such as smart homes, ubiquitous environment, and intelligent space (iSpace) have become popular [1]–[3]. This type of space is no longer merely an abstract concept realized in sophisticated research centers ; it is being widely implemented even in ordinary homes. The fundamental premise of these spaces is to increase the intelligence of the devices contained within, allowing them to provide users with more valuable information and services. However, the methods by which devices interact with the users vary according to the space. For example, in an iSpace [1], each device is treated as a distributed intelligent network device (DIND) and is connected to the same local network. Here, a DIND can be either an input device (e.g., a camera or microphone) or an output device (e.g., a projector, light, television, or speaker). An input DIND is used to capture the demands of the user or the current state of the space. Then, the captured data are transmitted to a server computer. After processing the data and determining an appropriate service, the server distributes this result to all DINDs. Finally, a single or multiple output DINDs, as specified by the server, provide service to the users.

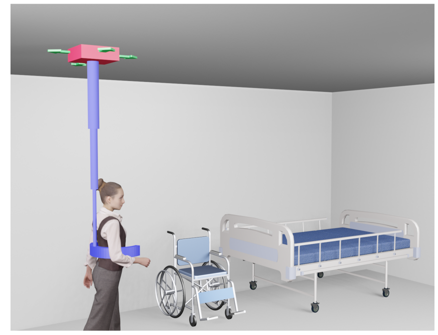
However, these spaces are either static or semi-dynamic and are not entirely oriented toward the users. In a static space, the poses (i.e., their positions and orientations) of all devices (e.g., DINDs in an iSpace) are fixed and do not automatically change. In contrast, in semi-dynamic space, the positions of devices are fixed but their orientations are variable. The simplest approach to transform a static device into a semi-dynamic state is attaching it to an actuator. Typically, the users must arrange devices in such spaces into optimal positions manually. Each time requesting a service, the user must consider the location of the device to obtain the most effective service. For instance, to watch television, the user must walk in front of a television. Furthermore, multiple devices are required to provide greater services to the users. For example, a home with multiple rooms needs multiple televisions, and detecting the users in any situation requires multiple cameras.

Due to the reasons stated above, fully dynamic spaces are required to provide higher quality and quantity of services. A fully dynamic space is known as a reconfigurable iSpace (R+iSpace). For an R+iSpace to be completely user-oriented, its devices must be able to move and rotate autonomously. This can be accomplished by mounting the devices using an on-ground robot or a wall-climbing robot. This eliminates the need for the user to move in order to watch television; rather, the television will move closer to the user. Moreover, by transforming a space into one that is fully dynamic, the number of devices required to provide valuable services is minimized

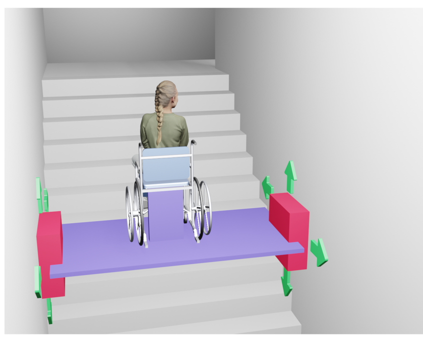


(a) Adaptive layout service.

(b) Indoor delivery service.



(c) Indoor walking assistance service.



(d) Indoor transportation service.

(e) Workflow monitoring service in the operating room.

Fig. 2. Several promising applications of MoMo in the future.

[4], [5]. In an iSpace, for instance, only one television is required because it can be moved between rooms.

As previously mentioned, there are two methods to convert a space to an R+iSpace. The first is mounting the devices on on-ground robots. In this method, the devices move on the floor alongside the robots. On the ground, however, there are numerous obstacles, including humans. These obstacles are challenging for the robots to avoid, as they may be dynamic or frequently change. Consequently, the algorithm for robot movement becomes extremely complex. In addition, the robots may negatively impact the users by obstructing their movement. Remarkably, due to the limited height of a standard on-ground robot, devices such as cameras and lights cannot cover a large area when mounted on the robots. For these reasons, this approach was not adopted for the development of R+iSpace.

On the other hand, the second method is employing wall-climbing robots that are capable of carrying devices and moving along the ceiling and wall (hereafter referred to as the field). The greatest advantages of this method are that the robots and mounted devices do not occupy any floor space, do not need to avoid numerous obstacles, and do not impede the users. Thus, the movement algorithm for robots becomes simpler. Furthermore, the devices, such as cameras and lights, can be positioned anywhere, allowing them to monitor a larger area. In light of this, the second method was adopted for building the R+iSpace.

Numerous climbing robots have been developed previously [6]–[28]. These robots can be categorized based on their adhesion or movement techniques. According to the adhesion techniques, they can be classified into four types: magnetic force [6]–[11], suction force [12]–[18], use of adhesive material [19]–[24], and mechanical adhesion [25]–[28]. In contrast, they can be categorized based on three movement techniques: walking by raising each leg individually [6]–[8], [12]–[15], [19]–[21], [25], driving using wheels [9], [16]–[18], [22], [23], [28], and moving with crawlers [10], [11], [24], [26], [27]. These robots were experimentally demonstrated to be capable of moving across a field without falling. However, these robots have numerous limitations, including slow movement, energy expenditure during idle state, insufficient loading capacity, and difficulty in self-localization.

In order to establish the R+iSpace, a novel climbing robot must be developed. The new robot is called mobile module (MoMo), which can move on the field and to which a device can be mounted (Fig. 1). Nevertheless, developing such a robot is extremely challenging. The MoMo must move efficiently on the field, not fall off the field, have a sufficient moving speed, not consume electricity when in the idle mode, have a large loading capacity, and precisely and simply self-localize. In addition to introducing several promising applications of the R+iSpace, this work provides an overview of all developed MoMos.

(a) MoMo 1 (b) MoMo 2

(c) MoMo 3

(d) MoMo 4.1 (e) MoMo 4.2

Fig. 3. Previous versions of the MoMo.

II. Promising Applications of Mobile Modules (MoMos)

As mentioned in Section I, the MoMo is significantly important for creating a fully user-oriented R+iSpace. By proposing such an R+iSpace utilizing MoMos, numerous user-oriented applications can be provided in the future. Fig. 2 illustrates several of these anticipated applications.

A. Adaptive Layout Service

The first promising application of the MoMo is adaptively customizing the layout of the R+iSpace and the properties (e.g., location) of available devices within this space. For instance, by attaching partitions to multiple MoMos, users can change the design of a room at any time (Fig. 2a). Moreover, when a user enters the space, devices connected to the MoMos, such as cameras, projectors, lights, televisions, and wall clocks, can be repositioned optimally. Typically, cameras can be moved to situations where users and their requests can be easily detected and recognized. Similarly, the position, display size, and display resolution of a projector can be adjusted in response to the status of the user. During a conversation between two or more users, using the cameras to detect eye movements, the lights can be moved to appropriate positions that better emphasize the object on which the users are focusing.

B. Indoor Delivery Service

Currently, conveyor belts and delivery robots are used in restaurants to deliver food and drinks directly from the kitchen to tables of customers. However, conveyor belts require space on the floor for installation. Moreover, delivery robots are predominantly ground-based. Such a robot must be capable of detecting humans, tables, and other obstacles placed on the ground to prevent collisions. Moreover, the appearance of such robots may annoy customers. Therefore, a robot that can move across the ceiling and walls without encountering obstacles to deliver food exhibits advantages such as ease of movement, conservation of floor space, and unobstructive operation. This robot can be developed using a single MoMo and an extendable robotic arm to pick up and drop off food (Fig. 2b).

C. Indoor Walking Assistance Service

The population in developed countries such as Japan is aging and declining. Consequently, many elderly people have problems with their spine, waist, or legs. These people have difficulty walking in everyday life and require devices to assist them in safely moving around. As a promising solution, a MoMo can be combined with an assistant module to aid elderly people in indoor environments (Fig. 2c). When compared to canes, crutches, walkers, and other walking mobility aids for older adults, a support device powered by MoMo will not require users to use their hands to control it. Sensors on the device can detect the direction of the user and transmit the acquired information to the MoMo. The MoMo then proceeds in this direction.

D. Indoor Transportation Service

Elevators and escalators are commonly used in commercial establishments, such as hotels, shopping centers, and high-rise structures. They are also used in private settings, such as private homes, particularly in homes with disabled residents. Given the size of a typical commercial space, the area required for an elevator or escalator is negligible. By contrast, individual locations are significantly smaller than commercial locations. Consequently, a relatively significant area is required to install a static elevator or escalator. Moreover, the installed devices are not as frequently used as they are in commercial spaces. Therefore, it is preferable to adopt a dynamic elevator in a private space rather than a fixed one. A dynamic elevator can be defined as a device that operates whenever users require it and frees the area in which it is located when not in use. As shown in Fig. 2d, two or more MoMos are utilized to construct such a flexible elevator. These MoMos carry a base plate on which the user can stand safely. With the ability of the MoMo to move on the field, the system can transport users in a manner similar to an elevator when in the active mode and move to the ceiling to free occupied space when in the inactive mode.

E. Workflow Monitoring Service in the Operating Room

For surveillance purposes, a minimal number of cameras can be attached to MoMos to allow them to move freely on the field (Fig. 2e). In this way, the camera system can monitor an R+iSpace, such as a private home, without encountering

TABLE I. Previous Mobile Module (MoMo) Specifications

	MoMo 1	MoMo 2	MoMo 3	MoMo 4.1	MoMo 4.2
Weight (kg)	1.45	2.55	1.60	1.70	1.90
Size (mm)	190x255x110	210x318x129	200x280x129	200x300x125	200x420x120
Actuators	8	5	4	4	3
Moving Speed (cm/s)	0.33	2.05	2.8	6.82	7.3

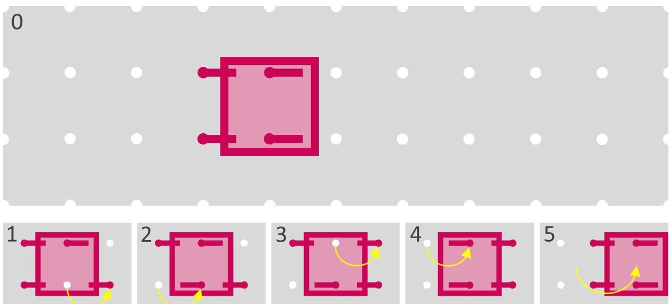


Fig. 4. Gait steps of MoMo 1.

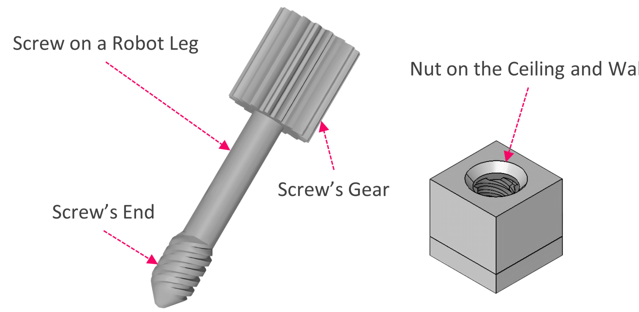


Fig. 5. Screw–nut mechanism in MoMos 1 and 2.

dead angles. Notably, such a system is more critical when monitoring the workflow in an operating room. For instance, the workflow monitoring systems in [4], [5], [29], [30] employed multiple cameras to capture every movement in the operating room. Then, the systems used these data to estimate the current workflow phase and detect unusual events that occurred during this phase. However, a surgical workflow is generally performed by a group of surgeons, with support staff gathered around a patient. Consequently, many dead angles may exist, and the critical motions that the cameras are unable to capture may be overlooked. By adopting MoMos in these situations, the attached cameras can be relocated to locations that provide a clearer view of both human and equipment movement.

III. Previous MoMo Versions and their Limitations

Since 2012, the R+iSpace, specifically the MoMo, has been the subject of extensive research [31]–[35]. Consequently, four prototypes of the MoMo were developed, excluding the version introduced in this study (refer to Fig. 3 and Table 1). These MoMos were proposed according to the following six design requirements: they must be able to move on both the ceiling and wall, their fall must be prevented by using a fastening mechanism, they must move sufficiently quickly, they must consume no energy when fastened and idle, they must have a high loading capacity, and they must be accurate and straightforward in their self-localization, as discussed in Section I. Before delving into the details of the latest MoMo version, this section provides a brief overview of previous versions and their limitations.

A. Screw–nut Mechanism–based Four-legged MoMo 1

The first MoMo was a four-legged walking robot capable of moving across the field (Fig. 3a) [31]. Each leg was composed of two actuators. One, referred to as a pinning actuator, was used to fasten and unfasten a leg to and from the field. The other, known as a panning actuator, was used to rotate the leg (gait steps 1, 2, 3, and 4) or the body (gait step 5) around the hip joint (refer to Fig. 4). This MoMo fastened and unfastened a leg to and from the field via a screw–nut mechanism controlled by the pinning actuator (Fig. 5). Each robot leg was equipped with a screw, and numerous nuts were evenly spaced across the vertical and horizontal axes of the field. The MoMo walked on the field by sequentially moving the four legs. Consequently, five gait steps were required to move from one position to the next, as illustrated in Fig. 4.

By adopting the screw–nut mechanism to fasten at least three of the four legs while in motion, the first MoMo was able to move on the field and effectively avoid falling. Additionally, once the robot tightened its screws into the nuts, it required no energy to maintain that position. This implies that the MoMo had zero energy consumption during any period of inactivity. Moreover, as each nut on the field had a fixed distance from the surrounding ones and the movement of each robot was restricted to this distance, the current location of the robot was measured quickly and accurately.

However, the first MoMo has several problems. The first and major limitation was the moving speed. In an experiment, it took 46 s for the robot to move 15 cm (approximately 0.33 cm/s) to the next position. This speed was insufficient for use in the R+iSpace. There are two possible explanations for this slow speed. The first and foremost reason was that the robot spent an inordinate amount of time fastening and unfastening the leg as a result of the screw-nut mechanism. The second reason was the length of time required to move the legs sequentially. The second limitation of the first MoMo was that the friction between a screw and a nut during fastening was experimentally shown to occasionally result in movement failure. The third was the high cost associated with the use of eight actuators.

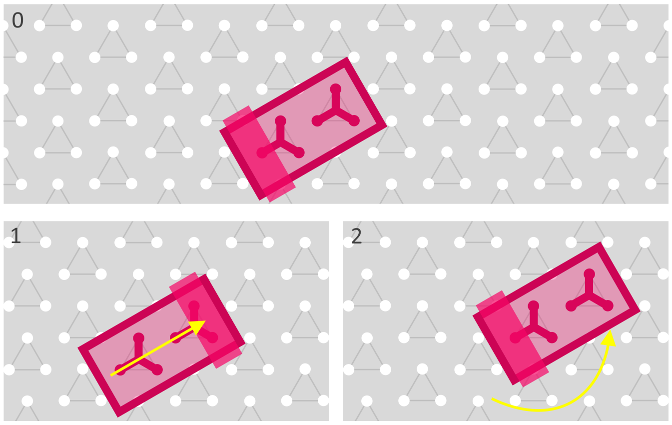


Fig. 6. Gait steps of MoMo 2.

B. Screw–nut Mechanism–based Two-legged MoMo 2

A second version was introduced to address the moving speed issue of the initial version (Fig. 3-b) [32]. Specifically, the number of legs was reduced to two. Each leg, similar to the legs in the first version, was equipped with two actuators called pinning and panning actuators. The screw–nut mechanism was also used in this version. Because of the limited number of legs in this robot, three screws in a triangular shape were attached to each leg to ensure that the robot had sufficient hinge force to free one leg and rotate its body around the other leg (gait step 2 in Fig. 6). The pinning actuator on each leg fastened or unfastened the screws simultaneously. The arrangement of the nuts on the field was thus altered to accommodate the screw structure. This MoMo added an additional component for mounting the device. A built-in actuator moved the component and device near one leg (gait step 1) before unfastening the other leg and rotating the body (gait step 2). Thus, the moment of inertia decreased dramatically with the rotation of the body. Consequently, MoMo 2 required only two gait steps to complete a movement (Fig. 6).

This version of the MoMo inherited all the advantages of MoMo 1, i.e., mobility without falling from the field, energy-free operation in the idle state, and efficient and precise localization. Moreover, by reducing the number of legs from four to two, the number of gait steps was reduced from five to two. Thus, the movement speed of the robot increased more than sixfold, from 0.33 cm/s to 2.05 cm/s. Additionally, this version utilized only five actuators, when compared to the eight required in MoMo 1, resulting in a decrease in the cost of the robot.

Although the movement speed of MoMo 2 was improved, it was extremely slow when deployed in practical applications. Apart from the reduction in speed caused by the screw–nut mechanism, the movement of the extra component between the two legs during gait step 1 also reduced the speed. Moreover, this version of MoMo lacked a device (e.g., a sensor) for tracking the location of screws on the legs in relation to nuts in the field. Experimentally, it was observed that a marginal error in positioning gradually resulted in screw abrasion. Consequently, incomplete leg fastening due to screw abrasion occurred occasionally. The incomplete fastening yielded a gap between the robot and the field. This gap led to an inability to fasten the other leg in the next gait step.

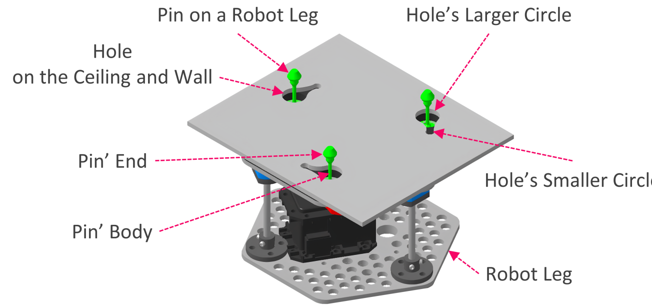


Fig. 7. Pin–lock mechanism in MoMo 3.

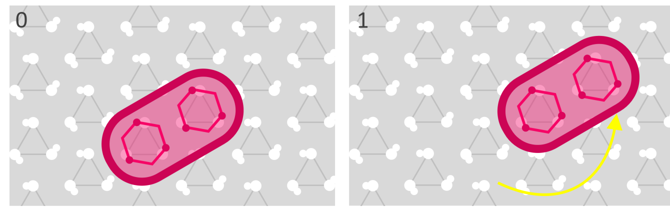


Fig. 8. Gait steps of MoMo 3.

C. Pin–lock Mechanism–based Two-legged MoMo 3

The third version of the MoMo was developed to overcome the issues raised in the second version (Fig. 3c) [33]. Two significant changes from the second MoMo were observed in this version. First, the screw–nut mechanism was replaced with a new one called pin–lock, as shown in Fig. 7. Specifically, the three screws were replaced with three pins on each robot leg. Each pin had a larger end and a smaller body. Moreover, the nut on the field was replaced with a hole formed by two circles of varying sizes. The fundamental concept of the pin–lock mechanism was to use the pinning actuator on a leg to simultaneously push three pins into the larger circles of the holes and then use the panning actuator to rotate them into the smaller circles to lock (i.e., fasten) the leg. The unlocking (i.e., unfastening) procedure was performed in the reverse order. Thus, the panning actuator served two roles in MoMo 3: rotating the body around one leg (similar to MoMo 2) and rotating the pins from the larger circle into the smaller one. Owing to the larger diameter of the end of the pin in comparison with the smaller diameter of the hole, the MoMo could avoid falling out of the field when locked. Second, the extra movable component where the device was attached was eliminated. Instead, the device was positioned at the center of the MoMo. Thus, the number of gait steps was reduced from two to one (Fig. 8). However, the removal of the extra component increased the moment of inertia of the robot during body rotation. To adapt to this, MoMo 3 replaced the panning actuator with one that had a higher torque than that used in MoMo 2.

By substituting the screw–nut mechanism with the new pin–lock mechanism and omitting the extra movable component to reduce one gait step, the moving speed of this MoMo was increased significantly from 2.05 to 2.8 cm/s. Moreover, the extra component necessitated the use of an actuator to

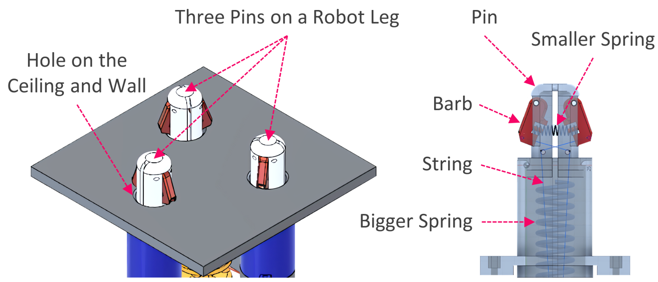


Fig. 9. Barb–spring mechanism in MoMo 4.

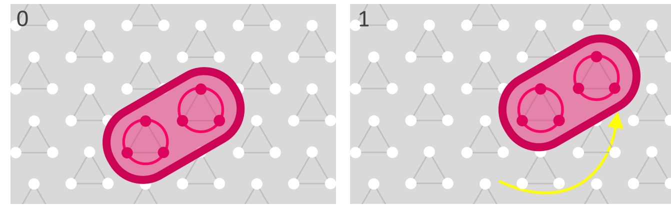


Fig. 10. Gait steps of MoMo 4.

translate between the two legs. Consequently, by eliminating this component, the required number of actuators was reduced from five to four, resulting in a reduction in the cost of the robot. Moreover, by ensuring that the larger circle of the hole has a diameter greater than the end of the pin, the MoMo could handle misalignment between the pin and hole caused by marginal positioning errors during the movement of the robot without the use of additional sensors. Thus, movement failure that occasionally occurred in the first and second MoMos was thoroughly overcome experimentally.

Nevertheless, several issues from the previous MoMos persisted. For example, although MoMo 3 could move faster than the previous two, its speed remained insufficient for adoption in the R+iSpace. Intuitively, the robot required approximately 3 min to move to a position 5 m away from the current one. Moreover, as previously stated, the panning actuator was replaced with a higher torque to accommodate the expansion in the moment of inertia. However, this replacement was insufficient to cope with the considerable torque generated by a heavy device (e.g., a television) attached to the robot.

D. Barb–spring Mechanism–based Two-legged MoMo 4

The fourth version of the MoMo was developed to further improve the speed of movement [34]. This version of the MoMo has two subversions (Fig. 3-d and 3-e). The first subversion (MoMo 4.1) was nearly identical to MoMo 3, except for the addition of a new barb–spring mechanism in place of the pin–lock mechanism (Fig. 9). The panning actuator was retained to enable rotation of the body of the MoMo around one leg. Conversely, the second subversion (MoMo 4.2) retained the barb–spring mechanism used in MoMo 4.1 but omitted the panning actuators of the two legs. Instead, it employed a wheel mechanism comprising an omni wheel that was controlled by an actuator. The wheel mechanism was attached between the two legs to allow the body of the robot to rotate around one leg. This reduced the number of required actuators. However, the gravity force acting on the robot caused a small gap between the robot and the field during its body rotation. Hence, a compressed spring was incorporated into the wheel mechanism to ensure that the wheel was always in contact with the field. Both subversions were equipped with the newly developed barb–spring mechanism, which accelerated the fastening and unfastening processes.

As mentioned previously, MoMo 3 rotated the pinning and panning actuators sequentially to push the pins on the leg into the larger circles and then rotated the pins into the smaller circles. These sequential actions, combined with the slow rotation of the actuator, resulted in low-speed fastening and unfastening processes. To address this, the barb–spring mechanism in MoMo 4 utilized compressed springs inside the pins to immediately push (by bigger springs) and lock (by smaller springs) the pins into the holes without the need for the effort of an actuator. However, the pinning actuator was required to unlock the pins and their barbs from the holes and compress the springs inside the pins. During the rotation of the body of the robot, the compressive state of the springs was naturally maintained by the resistive force from the field . Once the pins reached the holes, the resistive force was lost, and the pins were pushed into the holes automatically. Both robot subversions moved on the field by repeating a single gait step, similar to the third robot (Fig. 10). However, the gait step required fewer actions, and each action was significantly faster than that of MoMo 3.

As mentioned earlier, although MoMo 4 required only one gait step, the speed of the gait step was significantly faster than in the previous version. Consequently, there was a nearly threefold increase in the moving speed of the MoMo. Experimentally, MoMo 4.1 that used the omni wheel to rotate the body and MoMo 4.2 that used the panning actuator achieved speeds of 7.91 and 6.82 cm/s, respectively. In comparison, MoMo 3 had a speed of only 2.8 cm/s. It was observed that substituting the panning actuator with the omni wheel resulted in a faster speed. Additionally, by adopting the barb-spring mechanism rather than the pin–lock mechanism, the legs could be automatically fastened without the assistance of an actuator. Therefore, the roles of each actuator were reduced, resulting in energy savings.

However, several issues remain unresolved or resurfaced in this version. First, the loadable weight of the MoMo remained small and constrained owing to the elimination of the extra movable component. Second, because the pin used two barbs to lock it to the field, the body of the pin was required to have a diameter that corresponded to the diameter of the hole in the field (Fig. 9). Consequently, any misalignment between the pin and the hole could result in a fastening failure. This implies that the movement failure issue that was resolved in MoMo 3 reappeared in MoMo 4. Third, the primary reason for replacing two panning actuators with an omni wheel controlled by an actuator in MoMo 4.2 was to reduce the number of actuators required. However, the aforementioned movement failure occurred more frequently in MoMo 4.2 than in MoMo 4.1. This can be explained as follows. The compressed spring within the wheel mechanism generates a pushing force that acts on the field. By contrast, a reaction force of equal magnitude acted on the robot. Moreover, one leg was fastened, and the other was left free during body rotation. As a result of the reaction force, the gap between the robot and the field became more significant, and misalignment between the pins and holes occurred more frequently.

IV. Conclusion

Several future applications of R+iSpace and MoMo are presented in this paper to demonstrate that R+iSpace and MoMo research is extremely promising. Moreover, an overview of all developed MoMo versions was included. The developed MoMos satisfied four of the six design requirements. The robots were able to move on the field without collapsing. In addition, they required no electrical power to remain stationary in the field. Furthermore, they were able to precisely pinpoint their locations. However, the remaining two requirements (i.e., sufficient movement speed and large carrying capacity) were not met. Although the upgrade from the third to the fourth version of the MoMo significantly increased its speed, a faster MoMo was required for practical applications in the R+iSpace. Moreover, all versions of the MoMo were developed with the primary objective of increasing the speed of movement. The loading capacity was not taken into account during design or testing. None of the MoMos investigated the capacity of carrying weight. Additionally, movement failure due to pin–hole misalignment was a significant issue in these MoMos. These problems are open research questions for the future.

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