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Abstraction of the Body Ability of the Transformer Robot System for the Transportation and Installation of Heavy Objects in Land and Underwater Environments

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***Abstract*— To give the single robot system the ability to realize many behaviors and to realize tasks with shifting environments and objectives, it is necessary to abstract the robot's body ability to the extent that they can be detected by sensors in the body so that we can plan as the problem of state transition.**

In this paper, to abstract the transformer robot system that performs heavy lifting and environmental attachment tasks in an aquatic and terrestrial environment, we extend the graphical representation of the robot's body to manage joint capability and the body adaptability for the environment. To abstract the body ability, we divide the body into elements and define Connection between them at three different granularities. And using Connection, we propose the Connection Modification Feature(CMF) as the representation for changing body ability. To implement the Connection Modification Feature, we perform the abstract description and extract Connection to construct Body Ability Graph, a graph for the robot to manage its body ability. We show that it is possible to plan to manipulate and use its own Connection Modification Feature through multiple experiments by defining Normal Action that does not change body abilities and Body Ability Modifying Action that manipulate body abilities.

I. INTRODUCTION

In conventional robotics, a variety of robots exist depending on the environment and purpose, we configure them for individual uses. On the other hand, to give the single robot system the ability to realize a variety of behaviors and to realize tasks with shifting environments and objectives, it is necessary to abstract the robot's body ability to the extent that they can be detected by sensors in the body so that we can plan as the problem of state transition.

In this paper, to implement and evaluate a function that enables the robot to operate in multiple environments and for multiple purposes, we focus on the connection relationships among elements (environment, object, and robot) and propose features that manipulate them as the Connection Modification Feature(CMF). We divide Connection Modification Feature into three parts: Skeleton Modification Feature(SMF) between body elements, Joint Modification Feature(JMF) inside body elements, and Cover Modification Feature(CMF) on the surface of body elements. To manage state transitions across the CMF, we also present a stepwise state transition planning method.

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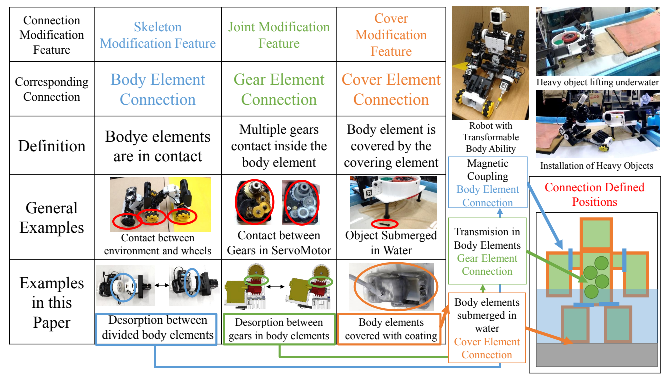

Fig. 1: Overview of abstraction of the body ability of transformer robot system.

II. RELATED WORK AND OUR CONTRIBUTION.

A. Related Work

Methods for abstracting and managing robot locomotion functions have been widely studied, especially for modular robots,[1], [2], [3]. In addition, there is a method that represents the body shape of a robot as a graph and searches for a body shape that can move by the environment by using a controller and a simulator at the same time. Our goal in this study is to extend the graph representation to the interior and surface of the body connection elements, in addition to the traditional body structures, to manipulate the joint functions and the adaptable environment.

Various configurations of joining mechanisms used to modify the body structure have also been proposed and are selected concerning the desired strength and detachment performance [4]. In this study, we introduced the connecting mechanism that is not equipped with an actuator but can be switched by an external magnetic force and detached[5]. And the robot system plan to change its body abilities based on the connecting mechanism. This study applies the methods related to motion realization capability and motion planning of multi-degree-of-freedom robots to a robotic system that changes body structure and body abilities.

Researchers have proposed many variable reduction mechanisms to switch the connection between gears and other drive links inside elements divided by a joint mechanism[6], [7]. In this study, we detect and manipulate the state between the actuator and output shaft of the drive shaft, using a mechanism that allows the joint to switch between the fixed and free states.

To adapt robots to the underwater environment, which is a familiar target environment, we use methods such as submerging the robot's entire body in water from the start[8] or adding a covering to a life-size robot that is normally inaccessible underwater[9]. In this study, we use a method of imparting the coating later with molten paraffin[10], which allows the robot itself to detect and manipulate the current state of the coating.

There is also PDDL(Planning Domain Definition Language)[11], which is used to solve planning problems by defining states and providing states, operations, initial and target states, etc., as input. In this study, we use Connection as a state to describe the body ability, including the content of the operation and constraints for execution, and perform motion planning including changes in the robot's body ability.

B. Our Contribution

We describe three contributions of this paper.

1) Proposal of representation and manipulation of Connection for abstraction of body ability
2) Development of the real robot system that detects Connection to determine the current bodily functions
3) Suggestion of the method of motion planning that includes changes in the body ability of the robot

We consider the robot body as the graph and proposed CMF that changes the covering state that determines the actionable environment, the body structure that determines the actionable movements, and the drive state that determines the joint functions. For that feature, we proposed the representation and modifying method to handle them with software via three types of Connection.

Next, for the three types of Connection, we configured a system that can detect the coating state by measuring temperature change, the body that can be divided and reconfigured by the robot, and the transmission mechanism that the robot can operate by itself. The features of this paper are that we have proposed a configuration method that can be easily introduced even for the multi-degree-of-freedom robot and a detection method for various states of the robot.

Finally, we have proposed the method to plan the entire motion by introducing Body Ability Modifying Action(BAMA) with Connection as the execution constraint and operation content. This method is characterized by extending the idea of state transitions in conventional motion planning and introducing it to the manipulation of body abilities. The contribution of this paper as a whole is that this method has enabled us to plan the entire process, including the changes in body abilities to perform the desired movements.

III. Expression and Operation for Abstraction of Transformable Body Capability

In this section, regarding Connection used in CMF, we show the classification of elements and the expression and description method of Connection, and organize the definition method of the element set required to extract the Connection.

We explain how to describe actions using Connection. Finally, we explain BAMA that corresponds to the three types of Connection.

A. Classification of elements in abstract description and definition of Connection.

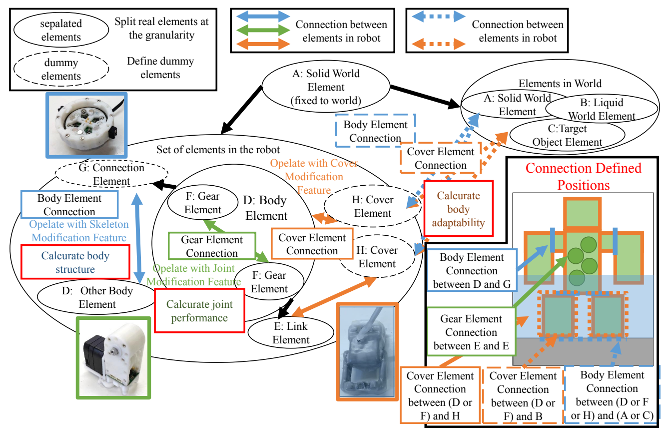

Fig. 2: Expression of connection based on the abstract description of the elements.

We show the classification of elements for the Abstract Description and the definition of Connection in Fig.2.

We classify the following eight types of elements in the Abstract Description.

A) Solid World Element
B) Liquid World Element
C) Target Object Element
D) Body Element
E) Link Element
F) Gear Element (simplified shape)
G) Connection Element (dummy shape)
H) Cover Element (summy shape)

A to E are those in which the real object has a geometric shape and spatial domain. F is defined in approximate form for a of Connection extraction if necessary. G has a dummy geometric shape for the definition of the coordinate system of Connection and geometric calculation. And H has no shape definition and H will be a connection element that is added by cover applying motion. In cases such as 6-8, where the description does not completely match the actual shape, or where the actual shape does not exist or is complex, the definition is simplified or eliminated, and we call this definition method the Abstract Description. As shown in Fig.2 shows Connection defined between elements, the defined points are inside and outside the body of the robot. Since the three types of Connection in the body determine the relationship between the robot's body structure, joint specs, and acceptable environment, we name the feature that manipulates them CMF.

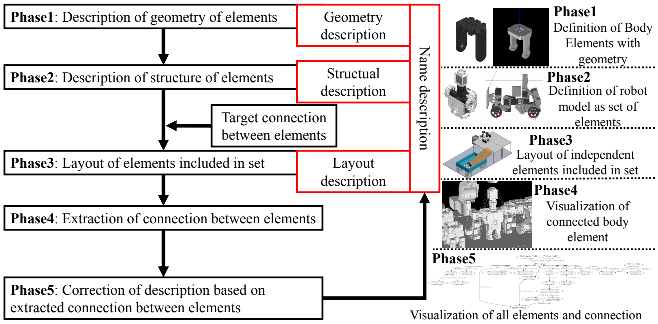

Fig. 3: Flow to define the set of elements.

B. Defining the set of Elements for extraction of Connection

We show the flow in defining the set of connected elements with the desired Connection in Fig.3. In Phase1, we describe geometry in euslisp[12], a geometric modeling language for programmable CAD, and geometric models for machine design. Phase2 corresponds to the description of the relationship between the elements defined in Phase1, and defines the whole body structure in typical robot modeling. It is also possible to refer to the constructed set by another set, e.g., a set of elements can be defined in the scene of a task, such as an environment model or a body element to be detached and attached. In Phase3, we make the spatial description of the individual connected elements within the degrees of freedom they can take, and the Connection extracted changes according to the description. Furthermore, in Phase4, the spatial connection/contact relationships among the elements also change as the arrangement of the elements changes according to the spatial arrangement description of the composed set. In Phase5, since Connection changes with each individual description, the description is modified to satisfy the target Connection while visualization is performed.

C. Representation of Body Ability Graph with Connection.

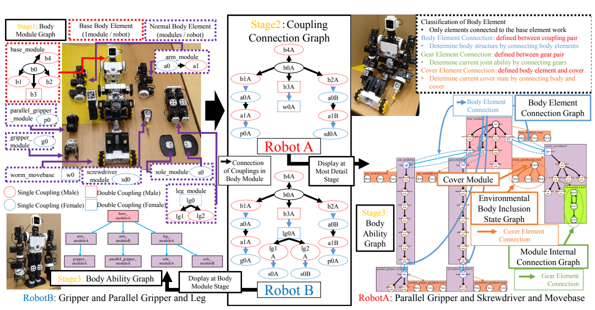

Fig. 4: Expression of Body Ability Graph describable by Connection between Elements.

We show the representation of Body Ability Graph that can be described by Connection in Fig.4. The Body Element corresponds to the elements that can be actively detached by the robot, and the Body Ability Graph corresponds to the Body Element connected. The set of Body Element is connected by edges corresponding to Body Element Connection to form Body Ability Graph, which is shown at the center of Fig.4.

The Body Ability Graph has Gear Element Connection and Cover Element Connection and classification of elements as states, and the state is defined and manipulated by the initial values given and the actions described below. An example of the notation of that graph is shown to the right of Fig.4.

D. Representation of Action describing constraints and operations with Connection.

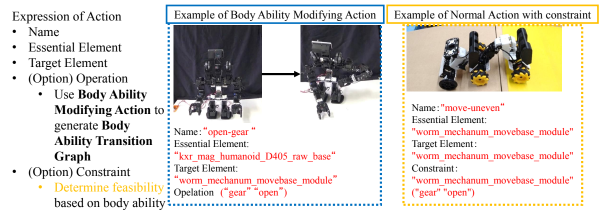

Fig. 5: Expression of Action describable by Connection.

We show the representation of the action in Fig.5 with Connection describing the operation content and constraints. The representation of the action has the following parameters: 1. Name, 2. Essential Elements for the action, 3. Target Element, 4. Operation Content, 5. A list of constraints on the elements when acting. Among these actions, those with descriptions that manipulate the robot's Connection are called Body Ability Modifying Action(BAMA), and the others are called Normal Action.

E. Connection Modification Feature for three types of Connection.

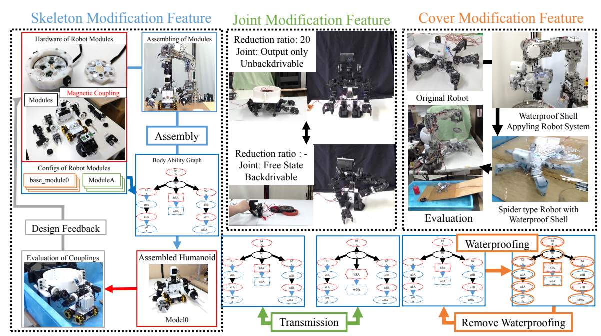

Fig. 6: Connection Modification Feature for three types of Connection.

In this section, we present CMF corresponding to the three types of Connection.

1) Skeleton Modification Feature for the environment of changing target behavior and body ability.: On the left side of the Fig.6, the robot is divided so that it can autonomously detach and detach the elements. We configure the system to configure and verify the robot using ALDMag to separate Body Elements. We uniquely determine the robot body structure by recognizing the connection direction of the elements and the elements in the internal communication system using the composite sensor board equipped with proximity sensors[13]. As an example of movement according to the body structure, we show the function of moving with the mecanum cart and the function of tightening the screw[5].

2) Joint Modification Feature for environments with fluctuating loads.: We show an example of switching between the drive state and the free state by configuring the operable meshing between the worm gear and the worm wheel in the center of the Fig.6 and having the human or robot switch between them. In the drive state, the self-locking function when the gears are engaged can hold joint loads caused by dead weight or external loads, enabling applications that are continuously loaded. In the free state, the output shaft can be driven by external forces by disengaging the gears, allowing for direct teaching and passive acclimation of the body to the environment.

3) Cover Modification Feature for aquatic and terrestrial environments.: We show an example of the operation of repeatedly dipping the small robot into molten paraffin to apply a coating to the surface after merging with the small robot using the life-size arm [10] so that the coating element be applied simply and densely on the right side of the Fig.6. To prevent the joints from sticking together, the small robot gains the ability to move underwater by continuing to move its joints while measuring the temperature until the paraffin, which was liquid, cools enough to harden.

IV. Hardware System for Handling Expression of Body Ability

In this section, we present the hardware system for the robot that can change its body functions while detecting the Connection of the body that is the subject of this research. First, we show the overview of the overall system, followed by a description of each of the actual elements that detect and operate the three types of Connection.

A. Overview of Hardware System

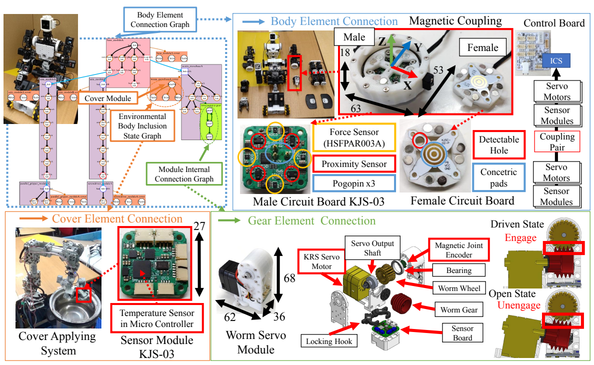

Fig. 7: Hardware System for Handling Expression of Body Ability.

We show the overview of the entire robot system in Fig.7. Each of the three types of Connection are handled in different hierarchies.

First, for the body modules divided by ALDMag[5], the body structure is determined by handling Connection between them, so it is necessary to recognize the type of module that the communication system contains and the connection direction.

Next, regarding the inside of the body element, since the joint drive function of the robot is determined by between the actuators and the links such as gears that exist between the joints, the current Connection is estimated by comparing the drive state at each of the actuators and the final output axis.

Since it is difficult to directly recognize the coating state on the surface of the body module, the temperature of the phase-changing paraffin is measured in this study using the temperature measurement function of a microcontroller to estimate it indirectly. In the following subsections, we will describe a system that detects and operates Connection in the following order: on the surface of the body modules, between body modules, and inside the body modules.

B. Detection and operation of Cover Element based on temperature measurement.

We show the detection and manipulation of the coating element in the lower left corner of the Fig.7. In this research, by using the temperature sensor of the STM32 microcontroller[14] equipped with the multiple sensor board[13] that the body contains, the temperature of the molten paraffin is measured, and the entry into the paraffin and the state of paraffin cooling and The state of the solid coating can be detected[10]. We set the target condition of the paraffin environment as the condition in which the temperature of the environment rises, and the target condition of the coating operation as the condition in which the temperature of the environment rises and then falls.

C. Determination and modification of body structure based on scanning of Body Element.

We show in the upper right corner of the Fig.7 the determination and modification of the body structure based on the scanning of elements. In this method, the robot can recognize the Body Elements that the current body contains by scanning the devices present in the communication system while de-energizing the Body Elements. In addition, since the interface between body elements is equipped with proximity sensors to recognize the direction of coalescence, the body structure can be determined, including recognition of the type of body elements[5].

D. Autonomous operation of Connection between Gear Element and recognition of input-output axis relationships.

We show the recognition of autonomously operable variable transmission mechanisms and input/output axis relationships in the lower right corner of Fig.7. In this method, we propose a mechanism that allows the robot itself to manipulate Connection between gears, and the mechanism is operated by the robot using an end-effector to switch body functions. In this mechanism, the actuator is rotated on a test basis and compared to the change in rotation angle at the encoder on the output shaft side to determine whether the present gears are connected or disconnected from each other.

V. Task Planning with Body Capability Management

We present the procedure to plan the experiment using Connection Modification Feature shown in Section III.

The experiment is planned through the following four steps.

- Stage1:Description of Set of Action
- Stage2:Automatic expansion of Body Ability Transition Graph
- Stage3:Expansion of Target Action Execution Graph and Path Search
- Stage4:Evaluation of the sequence of Actions and Scenes

In Stage 1, the robot's ability to operate is verified using a simulator and a real robot, using Connection corresponding to the three types of CMF as states and actions are described with Connection to include operation details and constraints. In Stage 2, we generate the Body Ability Transition Graph including all possible Body Ability automatically using BAMA described in Stage 1. In stage 3, we describe the task in the form of the Target Action Sequence and search for the path of Body Ability with Connection that can realize the action included in the sequence. In stage 4, we extract the transitions of Connection by describing the target sequence of task scenes to satisfy the transitions of the paths of the Body Ability explored in stage 3. The robot uses the transitions of Connection extracted in stage 4 to realize the experiment by mapping them to the transitions of Connection detected during the experiment.

A. *Stage1: Description of Set of Action based on verification results of Connection Modification Feature.*

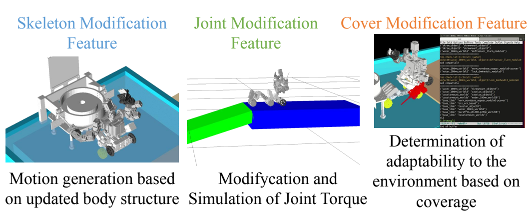

Fig. 8: Usage of embedded information of CMF.

We show how to use the CMF information embedded in the robot model in the Fig.8. In SMF, we construct the body geometric model based on Connection between body elements and inverse kinematics is solved using the geometric model of multiple connecting elements to generate motion. In JMF, the reduction ratio of the gear and the possible states of Connection are embedded, and the maximum torque of the robot model is switched according to the drive state for simulation. In CMF, the material information of the individual links and environmental elements is embedded to determine the feasibility of motion based on the compatibility of the materials and environment.

By using the above three types of CMF, we can verify in advance 1. the body structure that can achieve the target motion trajectory, 2. the joint functions that can execute the target motion, and 3. the motion trajectory that can be executed in the target environment. In addition, we use the real robot with three types of CMF and describe them based on the results of both simulation and real machine verification.

B. *Stage2: Automatic expansion of Body Ability Transition Graph based on Description of Set of Action.*

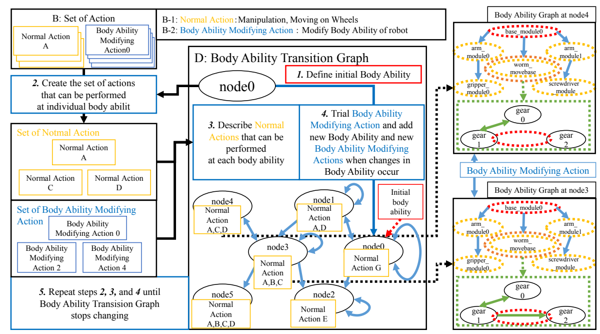

Fig. 9: Automatic expansion of Body Ability Transition Graph based on Set of Action and Target Action Sequence.

We show the procedure to automatically expand Body Ability Transition Graph in Fig.9. First, in 1, we define the initial Body Ability freely. Next, in step 2, the set of actions that can be performed at the Body Ability is created based on the description. Next, 3 and 4 are performed collectively. In 4, the new Body Ability and edge are added if the executable BAMA is executed on that Body Ability Node and it transitions to a new state quantity compared to all existing Body Ability Node. If it transitions to an existing node, only edges are added. Finally, repeat 2,3 and 4 until the conditions shown in 5 are satisfied.

C. *Stage3: Expansion of Target Action Execution Graph for pathfinding of body ability transitions.*

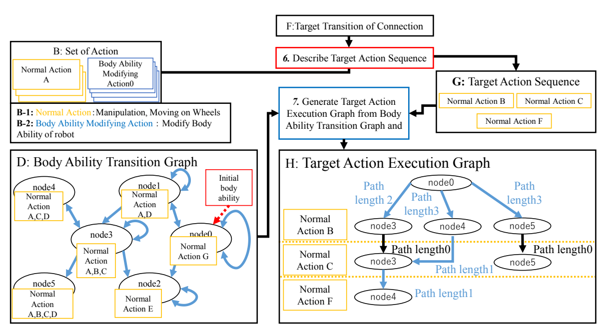

Fig. 10: Expansion of Target Action Execution Graph.

We show a method for generating a target action sequence realization graph in the upper right corner of the Fig.10. First, for 6, we write down the sequence of actions in completing the target task, where the actions are selected from the existing actions that have already been described and arranged in the order in which they are executed in the task. Next, for 7, by creating a set of Body Ability

Node for each goal action and connecting the paths in Body Ability Graph between the sets, the system generates the goal action sequence realization graph shown in Fig.9. For 8, there may be more than one pathway that satisfies the target action sequence, as there are two pathways in Target Action Execution Graph(TAEG) that can execute all three actions in the figure example, details of which are shown in stage 4.

D. Stage4: Evaluation of the feasibility of transition of Body Ability and create the sequence of Actions and Scenes.

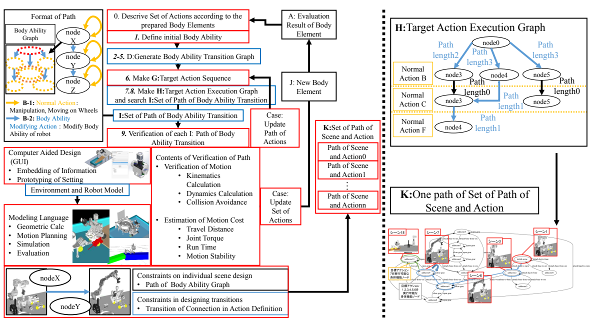

Fig. 11: Flow of designing Sequence of Scenes and Actions.

We show in Fig.11 how to evaluate the feasibility of a pathway of Body Ability, modify assumptions, and create a scene sequence. As in the example of TAEG in Fig.10, there may be multiple routes that satisfy the target action sequence, and we need to evaluate each route. In this step, each of the individual pathways of Body Ability obtained by calculation is mutually verified using the following three methods.

- Method1:CAD-based design support
- Method2:Geometric modeling language
- Method3:Qualitative comparative verification of multiple pathways

In Method1, the simple prototype of the scene is created and information of Connection Modification Feature is embedded in the system, which is then used in Method2.

In Method2, scenes are represented in geometric modeling language, and evaluated through geometric calculation, motion generation, motion feasibility judgment, and simulation. Here, paths are evaluated by assessing the feasibility of the Body Ability in the path and whether transitions can be made to satisfy transitions of Connection between the scenes, and if feasible, we can create the motions of the actions connecting scenes.

In Method3, we determine the one to be adopted by comparing multiple scene action sequences obtained. Here, both quantitative evaluations such as travel distance and execution time obtained by simulators and qualitative evaluations such as safety of individual routes exist, so the solution to the scene action sequence is obtained by evaluating and selecting according to individual cases.

Then, extraction of Connection is performed for the obtained scene sequence to check whether the desired transition is achieved, and if necessary, the description is modified according to the flow shown in Subsection III-B.

VI. Experiment

A. Experiment1: Applying the Cover Element by Measuring the Temperature of the surrounding environment.

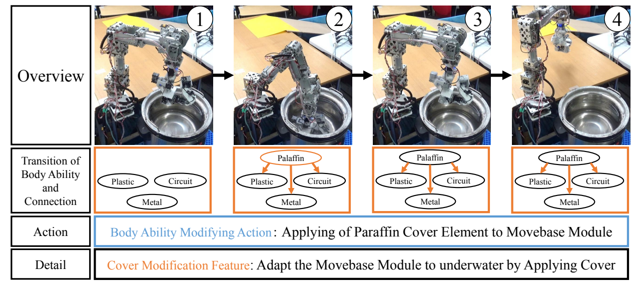

Fig. 12: Overview of the Experiment of Applying Cover Element to the Worm Movebase.

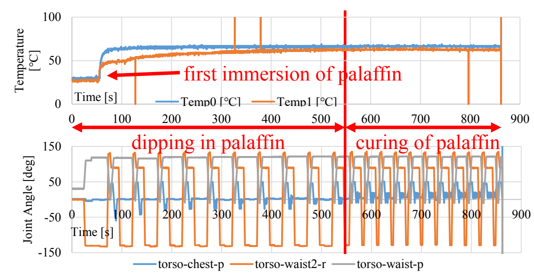

Fig. 13: Result of the Experiment of Applying Cover Element to the Worm Movebase.

We show the experiment in which the arm robot gives to the Worm Movebase in Fig.12. In this experiment, the arm robot and the Worm Movebase without wheels are connected via ALDMag, and the arm robot dips the Worm Movebase in paraffin and pulls it up in ① and ②. The Worm Movebase moves its joints until the coating hardens in ③ , and when the coating is ready, the arm robot transports the Worm Movebase to the tabletop in ④.

This experiment changed the Cover Element Connection of the material of the links that the Worm Movebase contains and is shown in Fig.12, which corresponds to Body Ability Modifying Action regarding Cover Modification Feature. As shown in Fig.13, the temperature measured by the sensor board KJS-03 shows that the Movebase is able to detect the state of being in the molten paraffin, and after the paraffin coating is given, the 850[s] after the paraffin coating is applied, the operation is continued to prevent joints from sticking.

B. Experiment2: Manipulation and Recognition of Body Structures in the Assembly of the small robot

In this experiment, the arm robot first starts the assembly operation at ①, the small robot attaches the gripper to its right wrist at ②, the upper body of the small robot and the carrying cart are combined at ③, and the small robot is separated at ④ to complete the assembly operation. This experiment corresponds to Body Ability Modifying Action on Skeleton Modification Feature, and we show the changes

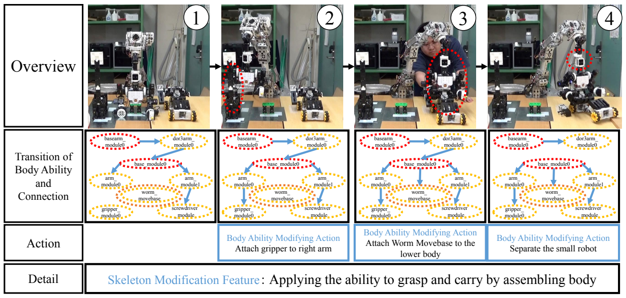

Fig. 14: Overview of the Experiment of assembling the Small Robot.

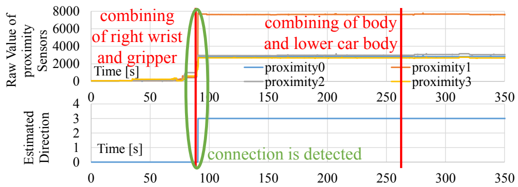

Fig. 15: Result of the Experiment of assembling the Small Robot.

of Body Ability Graph in Fig.14. In this experiment, we used the vision of the small robot to compensate for the relative position of the body elements and the hand tip placed in the real environment. Furthermore, as we show in Fig.15, the robot achieved to detect the connection to the gripper and its direction with the ALDMag on its right arm. We show the current visualization of the body structure in the video attachment.

C. Experiment3: Transporting and Installation of the Heavy Object.

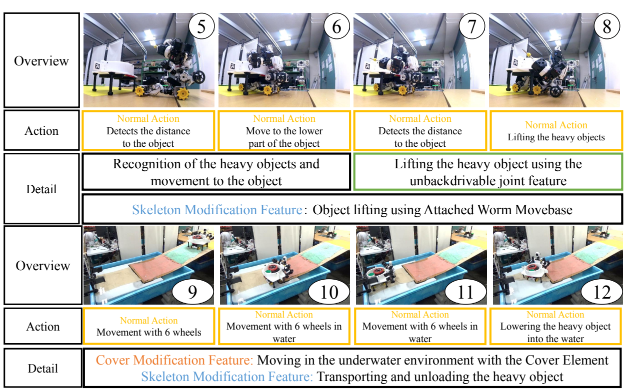

Fig. 16: Overview of the Experiment of transporting the heavy object.

As we show in Fig.16, the Worm Movebase uses the self-locking feature in the driven state in ⑤ – ⑧, so the action constraint describes that the waist axis is in the driven state. And the Worm Movebase that has been given moves from land to water in ⑨ – ⑫. In terms of the transition in the graph, the connection occurs between the Worm Movebase ($WORM_MOVEBASE$) and the underwater environment ($WATER_WORLDL$), but the Cover Element enables the movement in the underwater, and the object can be placed in the water.

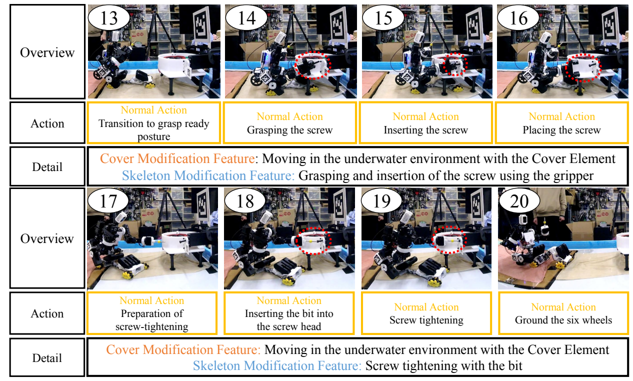

Fig. 17: Overview of the Experiment of installation of the heavy object.

The small robot achieves to insert the screw using the parallel gripper introduced by Skeleton Modification Feature in ⑬ – ⑯ and tighten the screw inserted with the bit of the left arm in ⑰ – ⑳. These movements are used to determine the possibility of end-effector movement in the underwater environment with Cover Modification Feature while generating the trajectory that does not allow the uncovered body to touch the water environment.

D. Experiment4: Modifying the Driving State of Joint for Moving over Rough Terrain.

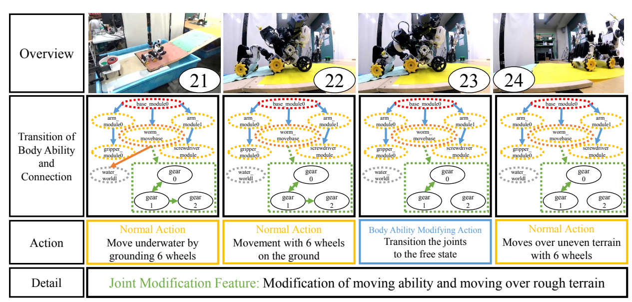

Fig. 18: Overview of the Experiment of modifying the driving state of Worm Movebase for moving over rough terrain.

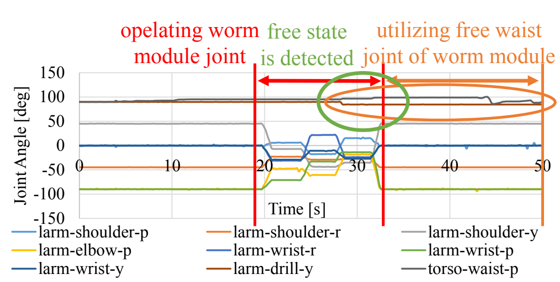

Fig. 19: Result of the Experiment of modifying the driving state of Worm Movebase for moving over rough terrain.

Finally in Fig.18, after the small robot pauses on the hill at ㉑ – ㉒, the small robot switches the drive state of the drive axes with bits at ㉓. This action corresponds to Body Ability Modifying Action regarding Skeleton Modification Feature and the Connection between the gears of the transport cart is changed.

The small robot uses the free state of Joint Modification Feature to allow the front wheels to touch passively in the environment, and the small robot moves over rough terrain with 6 wheels in ㉔. We describe the joints of the Worm Movebase in the free state as the constraint for this action. As we show in Fig.19, at the end of the movement to free the joint, the small robot detects that the current angle does not move significantly after moving the actuators of the joints, that is, it is in the free state. Based on the detected free state, the motion of moving over rough terrain is judged to be possible, and the experiment is continued to the end.

VII. Discussion

In this paper, we abstracted the Body Ability of the robot with Connection, configured the actual robot system capable of detecting its state, and proposed a method of motion planning including changes in the motor function, which enabled us to conduct experiments.

First, we discuss the abstraction of the Body Ability and its manipulation. Actions in experiments involving manipulation of body functions in Connection Modification Feature can be roughly classified into two types: 1: actions that change motor functions by manipulating Connection inside the body, and 2: actions that realize target movements by "using" actions made possible by Connection manipulation. The robot managed the transition to the target state by detecting 3:Connection in a way that corresponded to each. In Cover Modification Feature, by using the temperature measurement function of the microcontroller, which has already been distributed throughout the whole body, it was possible to detect the effect of penetration and coating on the molten paraffin simply. In Skeleton Modification Feature, by using the scanning and proximity sensors of the device including the communication system, it was possible to recognize whether the desired body structure was realized. In Joint Modification Feature, after the operation of the mechanism of the transport cart, the rotation angle of the drive shaft side was detected, and it was confirmed that the assumed drive state could be modified.

On the other hand, the entire methodology of this paper is based on the assumption that the description of actions is sufficient and reasonable. Therefore, there are issues such as whether the actions in Connection are sufficient enough to represent the state of the body that can execute the actions, and to what extent the actions can be described as similar actions in the first place. In reality, it is impossible to verify and describe actions for every case. We believe that when we add new elements, we will need a methodology that builds on assumptions that already exist and adds to them by verifying them concerning differences.

VIII. Conclusion

In this paper, to construct a transformational robot system that can adapt to multiple environments, we found that it is important to provide the robot with the ability to vary Connection between the drive links inside the body connection elements, between the environment and the connection elements, and between the body elements. To implement the functionality, it is also important to create a representation of the outline description so that Connection can be extracted, generate Body Ability Transition Graph to manage the hoge, and configure it so that it can operate and use its own Connection Modification Feature in a series of experiments. We have shown the importance of them through our integration experiments.

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