Kinematic Analysis for Task-Based Reconfiguration of Wheel-Arm Robots

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Abstract - **This paper presents the idea of reconfiguring multiple mobile-manipulator platforms called Wheel-Arm robots to increase their mobility and functionality. The Wheel-Arm robot is designed to be a wheel robot with a 4 DOF arm that has ability to manipulate small objects and move on flat terrain. The Wheel-Arm can also reconfigure itself to be a different type of one-wheel robot. By connecting multiple Wheel-Arm robots in different configurations, the robot group achieves different functionality. This paper provides kinematic analysis for various types of configurations which explains how the change in configuration affects their functionality including numbers of degrees of freedom for locomotion, manipulation, the ability to climb over obstacles and the maximum force exertion. These kinematic indices can be used in the task-based reconfiguration process which selects the configuration that best matches the given task requirements.**

I. INTRODUCTION

A mobile manipulator is a type of robot that can move and manipulate objects at the same time. Most designs of mobile manipulator usually complex and large. Kawakami et al. [1] proposed a new design for an SMC rover robot such that each wheel of the robot can be deployed from the main platform and becomes an individual one-wheel robot with an arm called a 'Uni-Rover'. From this design concept, a Uni-Rover has the ability to manipulate small object in the manipulation mode when it stands stably on the ground and has the ability to move with one wheel in the locomotion mode when it lies on the ground. However, the Uni-Rover can only have one functionality at a time which means it cannot move during the manipulation mode and cannot manipulate object during the locomotion mode. Furthermore, the one- wheel design that use a gripper as a supporting caster wheel during the locomotion mode makes it difficult for the robot to turn because of large friction at the big wheel and difficult to climb over obstacle due to the lack of driving force at the rear supporting wheel.

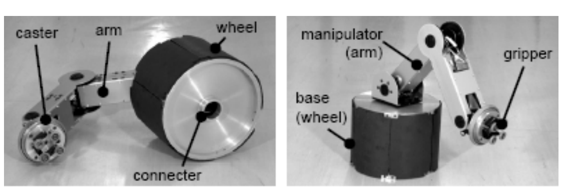

Fig. 1 Uni-Rover [Kawakumi et al. 2003]

Wheel-leg robot proposed by Quinn et al. [2] is designed to use legs attached to the wheel to improve mobility on rough terrain. However this type of robot is designed to use the leg mainly for locomotion purpose not manipulation.

There are numbers of researches on the increasing ability for a group of robots using group formation or reconfiguration, for example a Swarm-bots collective project proposed by Bonabeau, Dorigo and Therazulaz in 1999 [3]. The Swarm-bots comprised of a large numbers of small robots called an s-bot that can move freely and can also join together in the basic formation such as line. A joined group of Swarm-bots allows some additional functionalities that a single s-bot is not capable of such as crossing the gap that is larger than the size of a single s-bot. However the Swarm-bots design only allows one type of combined configuration which does not increase much of the locomotion or manipulation ability. Farritor and Dubowsky [4] proposed the method that use GA to select the design of a modular reconfiguration system. They used the hierarchical selection process to reduce the size of the search space.

The idea that is proposed in this paper is the design of a Wheel-Arm robot or a mobile manipulator. The Wheel-Arm robot can move freely by two drive wheels, can manipulate object using its arm and can be reconfigured into a one-wheeled robot or joined with other robots to create a two-wheel, a two-legged or a serpentine robot in order to achieve different types of locomotion ability. In the last section, the task-based configuration selection process that uses both quantitative and qualitative indices from the kinematic analysis is proposed.

II. MECHANISM DESIGN

The Wheel-Arm robot is designed to have two fixed wheels with one support caster wheel under a cylindrical body. The robot has a 4 DOF arm with gripper attached on the top of a cylindrical body as shown in Fig.2. When the robot lies down on the ground, its cylindrical body can be used as a drive wheel. The robot can be joined together with other robots by connecting the gripper with the knob under the cylindrical body or connecting the two knobs together to allow two arms to move freely and can be used to push or pull the body when climbing over large obstacle. The robot has 3 drive motors at its base, two for the small fixed wheel under the cylindrical body and one for the large wheel (i.e. the cylindrical body). The robot arm has 4 direct-drive motors connected directly to each joint and one motor for open and close the gripper at the end of the arm.

III. Possible Configurations

A. Single Robot

1) Type I (Manipulation mode)

In Type I configuration, which is also called the 'Manipulation mode', the robot is driven by two fixed wheels positioned underneath the cylindrical body with one support wheel. The arm with gripper has 4 degrees of freedom.

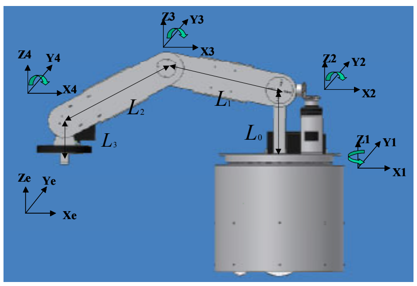

Fig 2. Type I (Manipulation Mode)

The kinematic model of this configuration can be separated into two parts between the wheel platform and the arm which are described in Equation (1) and (2) based on the analysis in [5].

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta}_0 \end{bmatrix} = \begin{bmatrix} -s_0 & 0 \\ c_0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -L_1 s_1 c_2 - L_2 s_1 c_{23} - L_3 s_1 c_{234} & -L_1 c_1 s_2 - L_2 c_1 s_{23} - L_3 c_1 s_{234} & -L_2 c_1 s_{23} - L_3 c_1 s_{234} & -L_3 c_1 s_{234} \\ L_1 c_1 c_2 + L_2 c_1 c_{23} + L_3 c_1 c_{234} & -L_1 s_1 s_2 - L_2 s_1 s_{23} - L_3 s_1 s_{234} & -L_2 s_1 s_{23} - L_3 s_1 s_{234} & -L_3 s_1 s_{234} \\ 0 & -L_1 c_2 - L_2 c_{23} - L_3 c_{234} & -L_2 c_{23} - L_3 c_{234} & -L_3 c_{234} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \quad (2)$$

The combination of wheel and arm posture kinematic model is described in Equation (3)

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\theta}_0 \end{bmatrix} = \begin{bmatrix} -s_0 & 0 & a_{13} & a_{14} & a_{15} & -L_3 c_1 s_{234} \\ c_0 & 0 & a_{23} & a_{24} & a_{25} & -L_3 s_1 s_{234} \\ 0 & 0 & 0 & a_{34} & a_{35} & -L_3 c_{234} \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \quad (3)$$

$a_{13} : (-L_1 s_1 c_2 - L_2 s_1 c_{23} - L_3 s_1 c_{234})$, $a_{14} : (-L_1 c_1 s_2 - L_2 c_1 s_{23} - L_3 c_1 s_{234})$

$a_{15} : (-L_2 c_1 s_{23} - L_3 c_1 s_{234})$, $a_{23} : (L_1 c_1 c_2 + L_2 c_1 c_{23} + L_3 c_1 c_{234})$

$a_{24} : (-L_1 s_1 s_2 - L_2 s_1 s_{23} - L_3 s_1 s_{234})$, $a_{25} : (-L_2 s_1 s_{23} - L_3 s_1 s_{234})$

$a_{34} : (-L_1 c_2 - L_2 c_{23} - L_3 c_{234})$, $a_{35} : (-L_2 c_{23} - L_3 c_{234})$

2) Type II.1, II.2 and II.3 (Locomotion mode)

Type II configuration, which is also called the 'Locomotion mode', is the configuration where the cylindrical body lies on its side and becomes a single large wheel. This type can be divided into 3 subtypes comprised of

- Type II.1 The gripper is not touching the ground. The robot becomes a one-wheel robot which is similar to a one-wheel bicycle.

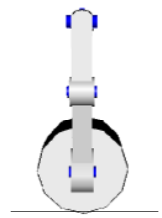

Fig 3. Type II.1

- Type II.2 The gripper touches the ground and becomes a support wheel with fixed orientation whose axis is always parallel to the axis of the large wheel and only allows the robot to move in straight line.

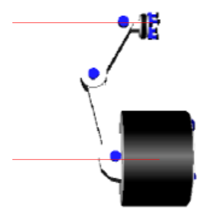

Fig 4. Type II.2

- Type II.3 The gripper touches the ground and becomes a caster wheel with can be oriented at different angles and allows the robot to turn to any direction.

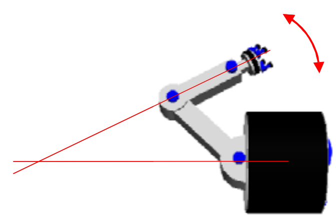

Fig 5. Type II.3

The posture kinematic model of Type II configuration can be found in the same way as in Type I as shown in Equation (4-5). The combined kinematic model of the Type II configuration is shown in Equation (6)

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} c_0 \\ s_0 \\ 0 \end{bmatrix} \begin{bmatrix} \eta_1 \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & -c_0 L_3 c_1 s_{234} & -s_0 L_3 c_{234} \\ b_{21} & b_{22} & b_{23} & -L_3 s_1 s_{234} & \\ b_{31} & b_{32} & b_{33} & s_0 L_3 c_1 s_{234} & -c_0 L_3 c_{234} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \quad (5)$$

$b_{11} : c_0 (-L_1 s_1 c_2 - L_2 s_1 c_{23} - L_3 s_1 c_{234})$

$b_{12}: c_0(-L_1c_1s_2 - L_2c_1s_{23} - L_3c_1s_{234}) + s_0(-L_1c_2 - L_2c_{23} - L_3c_{234})$

$b_{13}: c_0(-L_2c_1s_{23} - L_3c_1s_{234}) + s_0(-L_2c_{23} - L_3c_{234})$

$b_{21}: (L_1c_1c_2 + L_2c_1c_{23} + L_3c_1c_{234})$, $b_{22}: (-L_1s_1s_2 - L_2s_1s_{23} - L_3s_1s_{234})$,

$b_{23}: (-L_2s_1s_{23} - L_3s_1s_{234})$, $b_{31}: -s_0(-L_1s_1c_2 - L_2s_1c_{23} - L_3s_1c_{234})$

$b_{32}: -s_0(-L_1c_1s_2 - L_2c_1s_{23} - L_3c_1s_{234}) + c_0(-L_1c_2 - L_2c_{23} - L_3c_{234})$

$b_{33}: -s_0(-L_2c_1s_{23} - L_3c_1s_{234}) + c_0(-L_2c_{23} - L_3c_{234})$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} c_0 & c_{12} & c_{13} & c_{14} & -c\theta L_3c_1s_{234} - s\theta L_3c_{234} \\ s_0 & c_{22} & c_{23} & c_{24} & (-L_3s_1s_{234}) \\ 0 & c_{32} & c_{33} & c_{34} & s\theta L_3c_1s_{234} - c\theta L_3c_{234} \end{bmatrix} \begin{bmatrix} \eta_1 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \quad (6)$$

$c_{12}: c_0(-L_1s_1c_2 - L_2s_1c_{23} - L_3s_1c_{234})$

$c_{13}: c_0(-L_1c_1s_2 - L_2c_1s_{23} - L_3c_1s_{234}) + s_0(-L_1c_2 - L_2c_{23} - L_3c_{234})$

$c_{14}: c_0(-L_2c_1s_{23} - L_3c_1s_{234}) + s_0(-L_2c_{23} - L_3c_{234})$

$c_{22}: (L_1c_1c_2 + L_2c_1c_{23} + L_3c_1c_{234})$

$c_{23}: (-L_1s_1s_2 - L_2s_1s_{23} - L_3s_1s_{234})$, $c_{24}: (-L_2s_1s_{23} - L_3s_1s_{234})$

$c_{32}: -s_0(-L_1s_1c_2 - L_2s_1c_{23} - L_3s_1c_{234})$

$c_{33}: -s_0(-L_1c_1s_2 - L_2c_1s_{23} - L_3c_1s_{234}) + c_0(-L_1c_2 - L_2c_{23} - L_3c_{234})$

$c_{34}: -s_0(-L_2c_1s_{23} - L_3c_1s_{234}) + c_0(-L_2c_{23} - L_3c_{234})$

B. Two Robots

1) Type III (Push mode)

With this type of configuration, one robot in Type I configuration pushes the other robot which is in Type II configuration. This type of configuration allows the robot which is in Type II configuration to be pushed and climbed over large obstacle by the driving force provided by the pusher robot of Type I configuration.

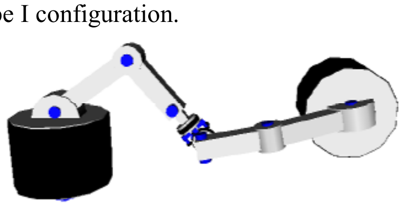

Fig 6.Type III (Push mode)

The kinematic constraint of Type III configuration can be described by Equation (7) where X_1, X_2 are the end-effector position of robot 1 and 2 consecutively, X_{r2} is the origin of the base frame of robot 2. Frame 0 is defined at the base frame of robot 1.

$$\begin{bmatrix} {}^0x_1 \\ {}^0y_1 \\ {}^0z_1 \end{bmatrix} = \begin{bmatrix} {}^0x_{r2} \\ {}^0y_{r2} \\ {}^0z_{r2} \end{bmatrix} + \begin{bmatrix} {}^{r2}x_2 \\ {}^{r2}y_2 \\ {}^{r2}z_2 \end{bmatrix} \quad (7)$$

2) Type IV.1 and IV.2 (Two-wheel mode)

Type IV configuration is a two-wheel mode which both robot lies on its side and two large wheels are joined by two rippers that connect to the knob under the other robot to create a closed chain mechanism. This configuration is similar to a motorcycle with two large front and back wheels that allows the robot to climb over a large obstacle by a driving force from both the front and the rear axles of the wheels. This configuration can also be divided into two subtypes.

- Type IV.1 is when the orientation of both wheels are fixed and have axis that is parallel to each other such that the robot can move only in a straight line.

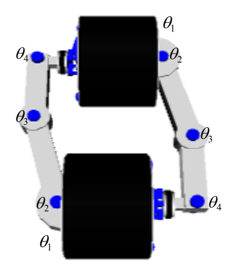

Fig 7. Type IV.1

- Type IV.2 is when both wheels can be oriented in any angle relative to each other and allow the robot to be steered in any direction by adjusting the joint variables of the two arms.

The kinematic constraint of Type IV configuration can be described by Equation (8) and (9). These constraints describe the closed chain condition when the end-effector position of robot 2 is at the origin on the base frame 0.

$$\begin{bmatrix} {}^0x_1 \\ {}^0y_1 \\ {}^0z_1 \end{bmatrix} = \begin{bmatrix} {}^0x_{r2} \\ {}^0y_{r2} \\ {}^0z_{r2} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} {}^0x_{r2} \\ {}^0y_{r2} \\ {}^0z_{r2} \end{bmatrix} + \begin{bmatrix} {}^{r2}x_2 \\ {}^{r2}y_2 \\ {}^{r2}z_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (9)$$

3) Type V (Two-arm mode)

Type V configuration is when the two robot are joined by connecting the knob under the cylindrical body together to create a two-arm robot with two large drive wheels. With this type of configuration, the robot can use its arm to manipulate objects or use it to push or pull its body when climbing a large obstacle.

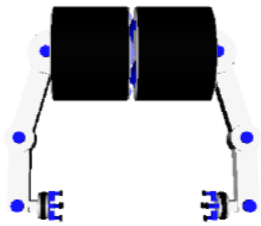

Fig 8.Type V (Two-arm mode)

The constraint Equation (10) describes the condition where the base frame of robot 1 and 2 are both at the origin of the base frame {0}.

$$\begin{bmatrix} {}^{0}x_{r1} \\ {}^{0}y_{r1} \\ {}^{0}z_{r1} \end{bmatrix} = \begin{bmatrix} {}^{0}x_{r2} \\ {}^{0}y_{r2} \\ {}^{0}z_{r2} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

4) Type VI (Serpentine mode)

Type VI configuration or the 'Serpentine mode' is the configuration where two robots are joined by one gripper that connects to the knob under a robot to create an open-chain mechanism. With this mode, the robot can move by using the frictional force constraint at the joint and create the serpentine-like motion. However, it is only suitable for traveling on a flat surface with the uniform and sufficiently high coefficient of friction.

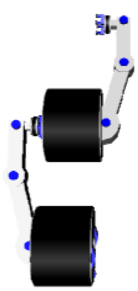

Fig 9. Type VI (Serpentine mode)

Equation (11) describes the constraint where the base frame of robot 2 is at the end-effector position of robot 1 but does not create close-chain condition as in Type IV case.

$$\begin{bmatrix} {}^{0}x_{1} \\ {}^{0}y_{1} \\ {}^{0}z_{1} \end{bmatrix} = \begin{bmatrix} {}^{0}x_{r2} \\ {}^{0}y_{r2} \\ {}^{0}z_{r2} \end{bmatrix} \tag{11}$$

IV. Kinematic Analysis

The kinematic analysis is performed to establish indices that can be used as a selection criterion for finding the suitable robot configuration for a particular task. These indices are

A. Degree of Manipulability

The number of degree of freedom that exists for the robot in order to manipulate objects depends on its Type configuration. In some configuration, such as Type II configuration, the robot can only manipulate object in two degree of freedom. Under Type I configuration, the robot has the maximum number of manipulability DOFs because its arm can be fully utilized in 4 DOFs. In Type III and IV, the robot sacrifices its manipulability DOFs for better mobility performance.

B. Degree of Mobility

The number of degree of freedom for motion on the plane for each configuration is derived from the reduced number of unconstrained generalized coordinates due to the number of non-integrable velocity constraints or the nonholonomic constraints present at each configuration. The maximum degree of mobility of all possible configurations is two because of the nonholonomic constraint that exists perpendicular to the wheel plane. In some configurations such as the locomotion mode (Type II.1 and II.2), Type III, Iv.1 and V, the degree of mobility is reduced to one because the robot can only travel in a straight line. In Type II.3 and IV.2, the robot can use its arm as a steering actuator as long as the robot satisfies its configuration constraint.

C. Stability

Stability of a mobile robot is the ability to balance itself on the ground surface. Static stability is defined when the center of gravity of the robot is within the convex hull of its polygonal support created from its contact with the ground. Type II.1 is the only case that the robot is not statically stable. With this type, the robot only creates a line contact with the ground. The quantitative measurement of stability can be found by measuring the minimum angle between the gravitational force vector that acts on the tipping axis that is defined along the side of its polygonal support [5]. In Type I, II.2 and II.3, the robot has a triangular support polygon. In Type III, IV, V and VI, the robot has a rectangular support polygon.

D. Climbing over & under obstacle/ Crossing gap

The ability to go over and under obstacle or to cross the gap, small hole and groove depends on the total width, height and length of the robot group. The ability to go over obstacle is evaluated from the active wheel radius and driving force of the wheels. In Type V, the robot has the highest ability to go over obstacle because it has driving force from 2 big drive wheels and two arms that can push or pull the robot to climb over obstacle. The ability of go under obstacle is evaluated by the total minimum height of the robot group. In Type II.1, the robot has the lowest ability of go under obstacle because it has to adjust the arm configuration to balance itself. The ability to cross the gap is evaluated from the distance between each ground contact and the driving force from the back support wheel. Type III has the highest ability to cross the gap because the distance between the ground contact of the two robots is very large and the pusher robot can provide the necessary driving force in order to cross the gap. In Type IV.1, the big wheel of the second robot provides the driving force of the back wheel that can push the first robot to the other side of the gap.

E. Force Exertion Capability

The maximum force that the robot can exert from each configuration is derived from the force creates by an arm, two small drive wheels and one big driving wheel. In Type I, the robot can only exert force from an arm and the two small drive wheels. In Type II, the maximum exertion force mainly comes from the big drive wheels. Type V has high maximum force exertion capability from two big drive wheels and two arms under the assumption that two drive wheels can rotate in synchronous.

All indices described above can be evaluated for each robot configuration type as shown in Table I.Variables in the Table are

H: height of the big wheel
J: joint thickness of the first joint
L: arm length
R: radius of the big wheel
r: radius of the small wheel under the robot
F: driving force of the big wheel
f: driving force of the small wheel
A: exertion force at the end-effector creates by arm joints

Type	Manipulability (DOF)	Mobility (DOF)	Stability	Ability to go over obstacle	Ability to go under obstacle	Crossing gap	Force Exertion
I	4	2	Triangular support	Low	H+J	<R	A+2f
II.1	2	1	Not-statically	Very Low	2R+L	<R	F
II.2	1	1	Triangular support	Low	2R	<2R	F
II.3	2	2	Triangular support	Low	2R	<2R	F
III	0	1	Rectangular support	High	H+J	<4R	A+2f+F
IV.1	0	1	Rectangular support	High	2R	<2R	2F
IV.2	0	2	Rectangular support	High	2R	<2R	2F
V	3	1	Rectangular	Very High	2R	<2R	2A+2F
VI	1	2	Rectangular support	Low	2R	<2R	<2F

TABLE I KINEMATIC EVALUATION FOR VARIOUS TYPE CONFIGURATION

V. TASK-BASED RECONFIGURATION PROCESS

From the kinematic analysis presented in the previous section, the robot configuration can be chosen according to the task requirements. However some types of indices are well quantified in number while some types are not within the scope of task requirements. For example the requirement for the maximum force exertion has a quantitative value, while it is difficult to specify the actual value of the stability margin of the terrain. Therefore, in order to reconfigure the robot based on the task, 2 steps are required in the configuration selection process. The first step is called 'the filtering process'. The filtering process will rule out the configuration that does not satisfy the quantitative requirements. The indices that are used in the filtering process are the number of manipulability degrees of freedom, the number of mobility degrees of freedom, the minimum ceiling height, the maximum gap width and the maximum exertion force. In this filtering process, any configuration that does not satisfy these quantitative requirements will be excluded from the search space.

The second step is called 'the heuristic decisioning process'. A set of fuzzy rules are defined based on the qualitative task requirements such as the terrain roughness which relates to the climbing ability and the ability to stabilized in addition to the manipulability and the mobility requirements.

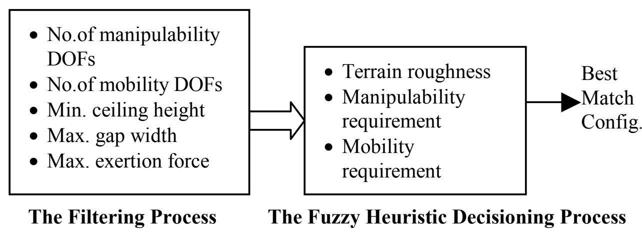

Fig 10. The configuration selection architecture

The fuzzy rules are defined as relations between the task requirement and the kinematic indices. For example the terrain roughness will have a direct relationship with the climbing ability and the stability of the type configuration. Fuzzy rules are constructed from 3 task requirements and 4 qualitative kinematic indices of each type configuration. Output of the fuzzy rule is the matching value between the task and each type configuration. The matching value for the group of rules that related to each requirement is defuzzified to be a quantitative value in the range of 0 to 1. The product of the matching values that are non-zero from the three requirements is calculated for each type configuration. The type configuration with the maximum product of matching values will be selected for the task.

Examples of fuzzy rules are

if the Terrain roughness is VERY HIGH and the Stability index is HIGH and the Climbing ability index is VERY HIGH then the Matching value is VERY HIGH

if Manipulability requirement is HIGH and Manipulability index is LOW then Matching value is VERY LOW

72 fuzzy rules are defined from the possible combinations of the related task requirements and the qualitative kinematic indices. These rules can be grouped into 3 groups that produce three matching value output: Terrain roughness requirement & Stability index & Climbing ability index (4x3x4), Manipulability requirement (MR) and Manipulability index (MI) (4x4) and Mobility requirement (MOR) and Mobility

index (MOI) (4x2). An example of the defined fuzzy rule Table is shown in Table II and III.

MR\MI	V.LOW	LOW	HIGH	V.HIGH
V.LOW	V.HIGH	HIGH	LOW	LOW
LOW	LOW	V.HIGH	HIGH	LOW
HIGH	V.LOW	V.LOW	V.HIGH	HIGH
V.HIGH	V.LOW	V.LOW	V.LOW	V.HIGH

TABLE II TABLE OF FUZZY RULES THAT DEFINES THE RELATIONSHIP BETWEEN THE MANIPULABILITY REQUIREMENT AND THE MANIPULABILITY INDEX.

MOR \ MOI	LOW	HIGH
V.LOW	HIGH	LOW
LOW	LOW	HIGH
HIGH	LOW	HIGH
V.HIGH	LOW	HIGH

TABLE III TABLE OF FUZZY RULES THAT DEFINES THE RELATIONSHIP BETWEEN THE MOBILITY REQUIREMENT AND THE MOBILITY INDEX.

Example of the task-based reconfiguration process can be shown as follows:
The robot is required to travel with high mobility on the paved street that has the ditch of 10cm wide on the side and the step to the pavement level of 6 cm in height. The robot does not need to grab an object nor exerts force to any object. The known designed parameters of the robot are R=10cm, r=4cm. From these requirements, Type I and II.1 are eliminated in the filtering process because their gap crossing ability do not satisfy the requirements. In the second step, the heuristic decisioning process is performed for the other 7 type configurations. The membership function for the terrain roughness is defined as the triangular function, which is normalized to be a value from 0 to 1 based on the parameter R of the robot. The range of membership function of the terrain roughness is defined between 0 to 2R. Therefore, the quantitative value of the terrain roughness in this example is equal to 0.3. The manipulability requirement for the task is defined to be 0.1 and the mobility requirement is defined as 0.7. From the fuzzy decisioning process, the configuration of Type IV.2 is chosen from its highest output of the product of the matching value of 0.4069.

When different task requirements are specified as shown in Table VI, different type configuration (from all possible configurations without the filtering process) is selected corresponding to different requirements of the task from the maximum matching value.

Case	Terrain roughness	Manipulability requirement	Mobility requirement	Selected Type	Matching Value
1	0.3	0.1	0.7	IV.2	0.4069
2	0.3	0.8	0.2	V	0.1748
3	0.1	0.8	0.2	I*	0.2405*

TABLE VI SELECTED TYPE CONFIGURATION BASED ON THE MAXIMUM MATCHING VALUE FROM THE FUZZY HEURISTIC DECISIONING PROCESS.

* If the filtering process from the gap crossing requirement in the previous example is imposed, Type V will be selected instead with the matching value of 0.0939.

The two steps of the task-based reconfiguration process provides the necessary accuracy for configuration elimination while does not excessively restricted for the user in defining the task requirements in the qualitative terms. The configuration selection process can be done in the planner where the set of tasks is previously defined and the robot can perform the reconfiguration along with the execution of the series of tasks.

VI. CONCLUSION

The Wheel-Arm robot design proposed in this paper is the mechanism that allows more than one robot to reconfigure itself and join together in order to achieve various functions for different types of environment and task. The Wheel-Arm robot is a simple mobile manipulator that can reconfigure itself into different types of configuration ranging from a normal mobile manipulator with 4DOF arm to a one-wheel, a two-wheel and a serpentine-like robot. The kinematic analysis of each configuration provides better understanding for the usability and the difficulties in control and stabilization for each robot configuration. The kinematic analysis also shown that this proposed design was highly adaptable for the use in different types of environment and task. The task-based configuration selection process is proposed in two steps, the filtering process and the heuristic decisioning process. The appropriate type configuration of the robot can be chosen based on the defined kinematic indices. The proposed task-based configuration selection process provided the procedural method for the robot reconfiguration during the execution of the tasks.

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