Modular Cooperative Mobile Robots for Ventral Long Payload Transport and Obstacle Crossing

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Abstract. In this paper, a new architecture for cooperative all-terrain mobile robots is introduced. It consists in a poly-robot system called C^3*Bots AT/VLP* robot. It is formed by the association of two or more identical mono-robots with simple kinematics that makes a poly-robot system while using the payload as a connecting frame. The mono-robots are able to co-manipulate long objects whatever their length and mass and to transport them in unstructured environments. Each mono-robot has a manipulator with up to four degrees of freedom that can catch the payload on the ground and lift it for a ventral transportation mode. The paper presents several kinematics and an obstacle crossing process in eighteen stages that guarantee permanent stability of the poly-robot thanks to motions of the mono-robots with respect to the payload.

Key words: Cooperative Mobile Robots, Long Payload Ventral Transportation Mode, Obstacle Crossing.

1 Introduction

It is very important to have a transport robot at disposal in many situations such as work in a dangerous environment (nuclear power station) or delicate transport (transport of injured people on stretchers). In this case, robot must be able to manipulate and transport different forms of objects [1], to manoeuvre on irregular grounds and to cross obstacles [2]. The all terrain mobile robots were developed for planetary or dangerous area exploration. They have different architectures [3] [9] and locomotion modes [8] [5] but the same purposes: They must be able to roll on irregular or unstructured environment and to guarantee a minimum stability during a mission.In the literature, cooperative mobile robots for transport are often complex. They use many actuated joints and a sophisticated control system. The simpler ones must comply with many constraints on the payload and the environment such as Army Ant cooperative lifting robots [3]. In this paper, we present the synthesis of the cooperative C^3*Bots AT/VLP*(All-Terrain /Ventral Long Payload) mobile robot. Section 2 describes the resulting poly-robot, associating two or more identical mono-robots that connect directly to the payload for transporting it. Section 3 describe the kinematics of the mono-robot, particularly the required degrees of freedom for the ventral manipulator. In section 4, the mobilities are combined to present an obstacle-crossing process in eighteen stages with only two mono-robots, where stability is achieved by motions of the mono-robots with respect to the payload.

2 C^{3}Bots AT/VLP general architecture

The concept presented in this work is based on the *OpenWHEEL i3R* platform [5]. *OpenWHEEL i3R* contains two axles linked with a serial inter-axial mechanism using three simple revolute joints (one active central joint for warping and two passive joints for steering). Each axle contains two actuated wheels [5]. *OpenWHEEL i3R* has an original climbing process based on a serpentine movement and divided into nineteen stages. Each stage is produced by a movement of a joint or by a wheel contact being removed or regained. For the new *C^{3}Bots AT/VLP* robot, it was decided to design a new platform suitable for the ventral transport of long payloads and partially inspiring from *OpenWHEEL i3R* for stable obstacle crossing. *C^{3}Bots* is original by the concept of combining several identical mono-robots with simple kinematics that make a poly-robot system using the payload as a connecting frame. *C^{3}Bots AT/VLP* focuses particularly on the transport of long payloads. The stability of the platform is a necessary condition to perform the climbing process.

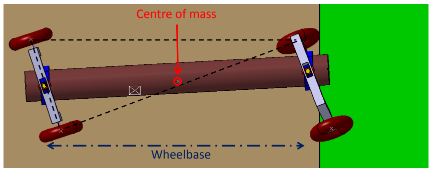

Fig. 1 Unstable configuration due to the Centre of mass on the edge of the lifting polygon of support of three contact points.

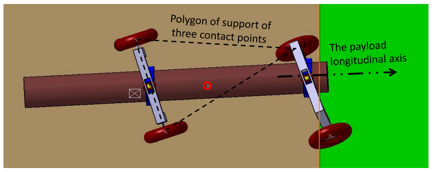

Fig. 2 Improvement of the stability thanks to the translation of the rear mono-robot along the payload.

Previous works [4, 6] showed that decreasing the wheelbase with respect to the track width increased the stability (Fig.1 and 2) on three wheels during stages $4-8-13-17$ of the climbing process presented in [6]. We also noticed that increasing the wheelbase reduced pitch variation when crossing an obstacle of a given height. Finally, crossing a high obstacle required to bring frontward the center of mass with respect to the contact points in order to equilibrate the crossing capacities of front and rear axles [7]. From these three remarks raised the necessity of a longitudinal translation mobility of the centre of mass with respect to the wheels (requirement $R1$). A second idea concerns the use of collaborative robots and led us to separate the initial *OpenWHEEL i3R* robot into two single axle mono-robots (requirement $R2$). By combining requirements $R1$ and $R2$ was born the *C^{3}Bots AT/VLP* (All-Terrain /Ventral Long Payload) robot concept using several single axle mono-robots able to catch the payload, translate along the payload longitudinal axis to change the wheelbase length and to rotate around their longitudinal axis to warp the poly-robot and elevate one wheel with respect to the others.

C^3*Bots AT/VLP* must be able to transport long payloads. To overcome the constraints related to the length of the transported payload, two or more cooperative mono-robots are used. The mono-robots are initially independent entities. Then, they connect to the payload, that becomes part of the resulting platform, called poly-robot (Fig.5). It should be note that some trucks dedicated to long payload transport also use the payload as a structural part [10]. The mono-robot cannot climb obstacles with its simple kinematic structure. But the poly-robot version can perform such an operation because the additional mobilities in the connecting chains can be used to generate relative motions between the mono-robot and the payload. In the next section, we present the mono-robot kinematic and poly-robot architecture.

3 Required mobilities and proposed kinematics

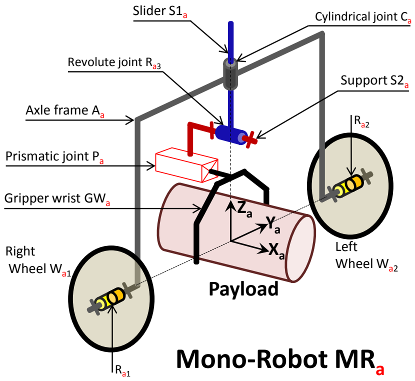

Fig. 3 Kinematic diagram of a mono-robot MR_a.

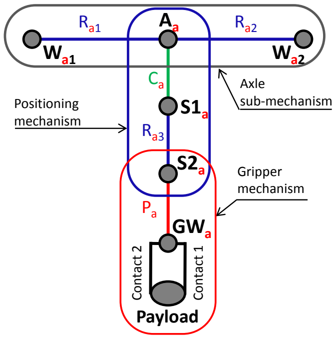

Fig. 4 Kinematic graph of a mono-robot MR_a.

The mono-robot includes an axle, a positioning mechanism and a gripping mechanism (Fig.3 and 4). The mono-robot, denoted MR_a, includes two wheels W_{a1} and W_{a2} motorized independently with two motors (with index ”a” equals to ”1” for front axle and ”2” for rear axle, ”1” for right wheel and ”2” for left wheel).To be able to manipulate the object, the robot is equipped with a gripper mounted at the bottom of the chassis. The originality of the concept lays on the kinematic chain of the positioning mechanism. The axle frame (A_a) can freely steer around the cylindrical joint C_a with respect to slider ($S1_a$). The remaining vertical motorized translation T_{za} of C_a allows controlling the altitude of the gripper and consequently of the payload. The roll motion R_{xa} between the slider body ($S1_a$) and the support body ($S2_a$)

is ensured by the revolute motorized joint (R_{a3}) which is compulsory to reproduce warping motion of one axle roughly around the longitudinal axis of the payload, as the original *OpenWHEEL i3R* did. During solo locomotion configuration, the mono-robot can transport small payload on flat ground. Stability can be obtained by several solution: active pitch control in the same way as [?] or adding a retractable arm with a passive caster wheel.

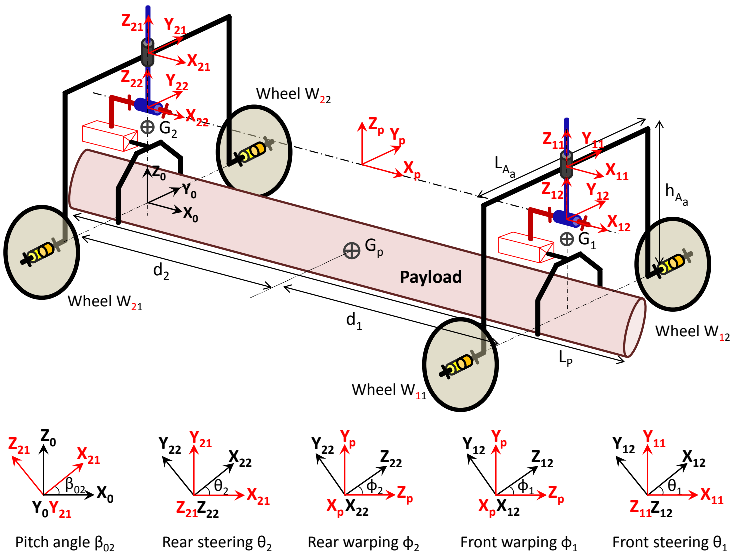

Fig. 5 Relative position of each frame and the associated angles.

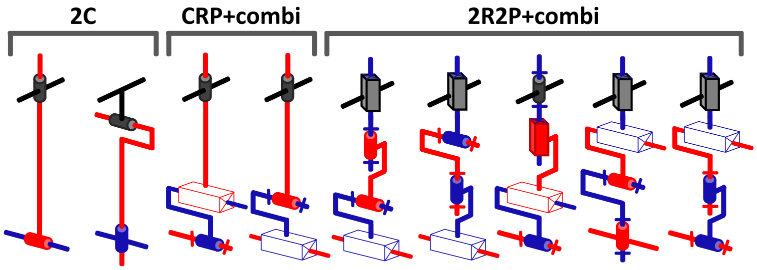

Fig. 6 Selection of equivalent joint combinations for producing the four required mobilities (T_{xa},T_{za},R_{xa},R_{za}) between axle and gripper.

The connection between the mono-robots is ensured by the transported payload as shown in Fig.5. The co-manipulation of the payload by the two mono-robots allows obstacle crossing. The poly-robot combines the mobilities of the mono-robots.

It can control the passive rotation R_{za} of the cylindrical joint (C_a) on each mono-robot by the difference of angular velocities of the two wheels of each axle. The redundant revolute joints R_{13} (front) and R_{23} (rear) give a warping degree of freedom to the poly-robot. When joints R_{a3} are actuated (either R_{13} or R_{23}), a warping motion is generated of one mono-robot around the joint R_{a3} axis with respect to the other mono-robot. This movement allows to lift the exploration wheel off the ground. We have therefore a new configuration of the system with only 3 wheel-ground contacts. Finally, prismatic joint P_a between gripper GW_a and support $S2_a$ in each mono-robot allows translating the mono-robot along the payload axis. Several equivalent serial kinematic chains are presented in Fig.6 and can be used for a real implementation. As a conclusion, the implementation shown in Fig.5 provides the four mobilities required on each mono-robot for stable payload transport and obstacle of the poly-robot:

- a rotation R_{xa} for wheel elevation on obstacles (R_{a3}).
- a rotation R_{za} for steering and stabilization on 3 wheels configuration (C_a).
- a translation T_{xa} for on improved stabilization with a long payload (P_a).
- a translation T_{za} for payload elevation (C_a).

4 Locomotion modes for obstacle crossing

In this section, two locomotion modes are described for obstacle crossing. We are interested in the case where two axles or more are used. First, the warping mode inspired by *OpenWHEEL i3R* is developed for two axles. Then, we describe the $2D$ crossing modes with three axles and more.

4.1 Two axles warping mode inspired by OpenWHEEL i3R

. The climbing process of the C^3*Bots AT/VLP* platform is an original process based on a *'serpentine'* movement. It is divided into eighteen manoeuvres within four phases (Fig.7). Each manoeuvre is achieved by the motion of a single joint or by a change in the contacts of wheels on the ground. We define a phase P as a series of manoeuvres M that conducts to crossing a wheel W_{as}. Thereby, there are four phases in the process along with some intermediate manoeuvres to rearrange the body of the robot. The phases are given representative names depending on the lifted wheel to lift during the phase. For example, $PW_{12}M_{02}$ is the second manoeuvre M_{02} of the phase referring to lifting the front left wheel W_{12}.

The climbing process starts by approaching the obstacle. We suppose that the first axle of the poly-robot is brought parallel to the obstacle and that the axle frames (A_1) and (A_2) are perpendicular to the payload axis. The mono-robots are in the extremity of the payload before starting the climbing process. The first phase consists in stepping over the obstacle with wheel W_{11}.

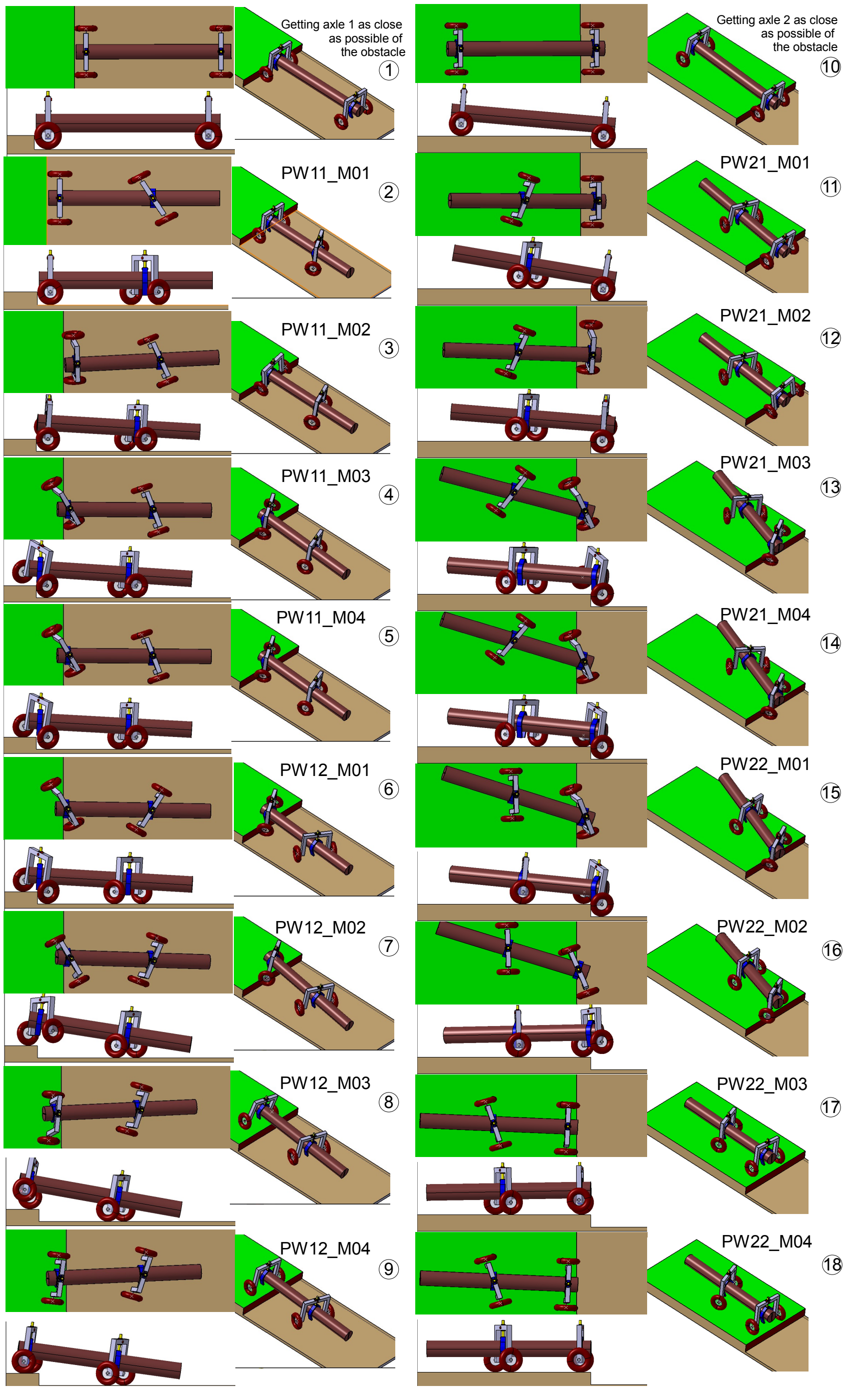

Fig. 7 Climbing sequence of the poly-robot with only two axles.

The first manoeuvre $PW_{11}M_{01}$ is made to find the optimal position of rear axle in order to prepare the lift-off of the exploring wheel with a maximum stability margin. In this manoeuvre we have to find two parameters: the distance between the mono-robots and the steering angle of the rear axle. Stability analysis and optimization of these parameters will be presented in a future work. Warping the front mono-robot lift-off the exploring wheel at manoeuvre $PW_{11}M_{02}$. At manoeuvre $PW_{11}M_{03}$, the rear wheels are actuated while the wheel W_{12} is locked. The exploring wheel passes over the obstacle by a steering motion of the front axle. Finally, the first phase is achieved by putting down the exploring wheel W_{11} at manoeuvre $PW_{11}M_{04}$. The same is done for W_{12} crossing in the phase PW_{12}, which starts at $PW_{12}M_{01}$ by finding the optimal position of the rear mono-robot and finishes by putting down the wheel on the obstacle at $PW_{12}M_{04}$. After finishing the two first phases, the front axle of the robot is on the obstacle. This time, the exploring wheel will be one from the rear axle (wheel W_{21} or W_{22}). So the first manoeuvre $PW_{21}M_{01}$ consists to bring forward the rear axle to the obstacle and to find the optimal position of front axle. After warping the rear mono-robot in the manoeuvre $PW_{21}M_{02}$, the front axle moves forward to bring the exploring wheel over the obstacle (manoeuvre $PW_{21}M_{03}$) and puts down the exploring wheel in the last manoeuvre $PW_{21}M_{04}$ of the third phase. The same is done for the last wheel W_{22}. The phase PW_{22} starts by finding the optimal steering position of the front mono-robot at manoeuvre $PW_{22}M_{01}$ and finishes by putting the wheel on the obstacle after manoeuvre $PW_{22}M_{04}$. Finally, the poly-robot rearranges the positions of the rear and front axles to find its standard configuration.

4.2 *Three axles and more $2D$ crossing modes*

The climbing process with three axles and more is very simple compared to the two axles configuration, because during the climbing process, the poly-robot has always two axles or more on the ground and one axle only is lifting off to climb obstacle. With three axles A_1, A_2, A_3, the climbing process starts by approaching the obstacle and moving forward A_2 to have the centre of mass of the payload between A_2 and A_3. After that, axle A_1 is raised. Then A_2 and A_3 are actuated to bring A_1 over the step. The axle A_1 is then put down on the step. The same is done for axles A_2 and A_3. Viewing different possible configurations for the robot, we can say as a general conclusion that the three axles (and more) configuration allows an easy obstacle crossing $2D$ mode at the price of high number of axles. For the final configuration, we recommend to use two mono-robot and the warping mode described in (4.1) as it requires a minimal number of mono-robot.

5 Conclusion and future work

In this paper, we proposed a new concept of cooperative mobile robots to deal with the problem of long object transportation in unstructured environment whatever the payload length. The proposed *C^3Bots AT/VLP* robot is formed by the association of two or more mono-robots with simple kinematics forming a poly-robot system. Using such a modular poly-robot provides interesting advantages such as easy adaptation to the task, fast maintenance by simple replacement of defective mono-robots and standardization of the mechatronics architecture and associated control. Moreover, the proposed poly-robot has crossing obstacle capabilities and can use a climbing mode inspired from the *OpenWHEEL i3R* mobile robot. As a perspective for this work, the optimization of the process for all the steps will be considered as well as the evaluation of the dynamic stability for critical configurations of the robots. This must be done to ensure a smooth transition between the steps of the process. By ensuring the stability of the payload and its position control, *C^3Bots AT/VLP* can transport sensitive payloads such as victims and hazardous equipments that must be maintained in a well-defined position.

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