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Hybrid Driving-Stepping Locomotion with the Wheeled-legged Robot Momaro

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***Abstract*— Locomotion in uneven terrain is important for a wide range of robotic applications, including Search&Rescue operations. Our mobile manipulation robot Momaro features a unique locomotion design consisting of four legs ending in pairs of steerable wheels, allowing the robot to omnidirectionally drive on sufficiently even terrain, step over obstacles, and also to overcome height differences by climbing. We demonstrate the feasibility and usefulness of this design on the example of the DARPA Robotics Challenge, where our team NimbRo Rescue solved seven out of eight tasks in only 34 minutes. We also introduce a method for semi-autonomous execution of weight-shifting and stepping actions based on a 2D heightmap generated from 3D laser data.**

I. Introduction

Locomotion in uneven terrain is important for a wide range of robotic applications, including Search&Rescue operations. On a mechanical level, most approaches fall either into the *wheeled* or the *legged* category. Wheeled systems, which include also tank-like tracked vehicles, are robust and facilitate fast planning, while being limited in the height differences or terrain types they can overcome. Legged systems require more effort to control and maintain stability, but can cope with quite difficult terrain, because they require only isolated safe footholds. On the downside, they often move slower than wheeled systems.

Hybrid systems with a combination of legs and wheels, namely legs ending in wheels, promise to combine the benefits of both locomotion modes. As long as the terrain allows, locomotion is done by driving on the wheels while adapting to slow terrain height changes with the legs. If larger obstacles prevent driving, the robot switches to stepping locomotion.

In addition to flexible locomotion, many applications also require dexterous manipulation capabilities. These result in additional requirements to the robot base, such as raising the robot manipulators to different heights. Furthermore, some domains require locomotion in restricted spaces, e.g. passing through doors or locomotion inside a vehicle. The combination of these requirements exclude many of the existing robot designs. Based on our previous work on domestic service robots [1], humanoid soccer robots [2], and rover-type mobile manipulation robots [3], we designed the mobile manipulation robot Momaro specifically for the set of requirements of the DARPA Robotics Challenge (DRC) [4].

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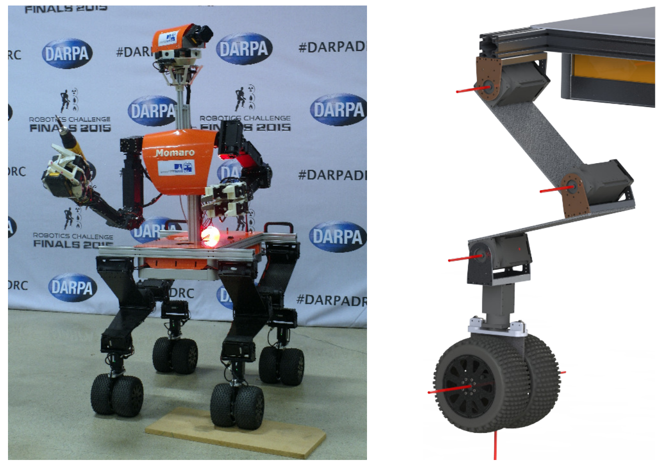

Fig. 1. Left: The mobile manipulation robot Momaro. Right: CAD rendering of the front left leg. The six joint axes in hip, knee, ankle pitch, ankle yaw and wheels are marked with red lines.

For flexible locomotion, Momaro is equipped with four articulated compliant legs that end in pairs of directly driven, steerable wheels. To perform a wide range of manipulation tasks, Momaro has an anthropomorphic upper body with two 7 DoF manipulators that end in dexterous grippers. Momaro is equipped with many sensors for environment perception, including a 3D laser scanner and seven cameras. Through the Momaro robot, our team NimbRo Rescue solved seven of the eight DRC tasks in only 34 minutes, coming in as best European team at the 4th place overall.

The main contributions of this paper are:

- design of a capable wheeled legged robot for complex mobile manipulation tasks,
- demonstrating the usability and flexibility of hybrid driving-stepping locomotion on the example of DARPA Robotics Challenge tasks, and
- proposing a basic step controller, which shifts weight and executes steps semi-automatically when required.

II. Related Work

The need of mobile manipulation has been addressed in the past with the development of a variety of mobile manipulation systems consisting of robotic arms installed on mobile bases with the mobility provided by wheels, tracks, or leg mechanisms. Several research projects exist which use purely wheeled locomotion for their robots [5], [6]. In previous work, we developed NimbRo Explorer [3], a six-wheeled robot equipped with a 7 DoF arm designed for mobile manipulation in the rough terrains encountered during planetary exploration.

Wheeled rovers provide optimal solutions for well-structured, and relatively flat environments, however, outside of these types of terrains, their mobility quickly reaches its limits. Often they can only overcome obstacles smaller than the size of their wheels. Compared to wheeled robots, legged robots are more complex to design, build, and control [7]–[10] but they have obvious mobility advantages when operating in unstructured terrains and environments. Some research groups have started investigating mobile robot designs which combine the advantages of both legged and wheeled locomotion using different coupling mechanisms between the wheels and legs [11]–[13]. Recently, the DRC accelerated the development of new mobile manipulation platforms aimed to address disaster response tasks and Search&Rescue operations. While the majority of the teams participating in the DRC Finals designed purely bipedal robots[1], four of the five best placed teams chose to combine legged with wheeled locomotion, which might indicate a superiority of this design approach for the challenge tasks. On the one hand, these robots can move fast over flat terrain using their wheels, on the other hand, they are able to overcome complicated terrain using stepping.

CHIMP [14], which placed 3rd in the DRC Finals, was designed to maintain static stability and avoid engineering challenges which arise if complex balancing control techniques are needed to maintain dynamic stability. Therefore, the roughly anthropomorphic robot is equipped with powered tracks on its arms and legs, which can be used to drive over uneven terrain. During manipulation tasks, CHIMP rests on the two tracks of its hind legs, which still provide stable mobility, but allows the robot to use its grippers to manipulate objects. In contrast to our concept, CHIMP does not execute any stepping motions to overcome bigger obstacles like stairs, but instead drives over them on its four tracks while maintaining a low center of mass to avoid falling. The user interface of CHIMP combines manual and autonomous control, for example by previewing candidate free-space motions to the operator.

Likewise, RoboSimian is a statically stable quadrupedal robot with an ape-like morphology [15], [16]. It is equipped with four generalized limbs consisting of seven joints each, which can be used for locomotion and manipulation. All of these 28 joints are driven by identical actuators to ease development and maintenance of the robot hardware. Furthermore, it is equipped with under-actuated hands at the end of its limbs with fewer digits and active DoF than a human hand. Besides executing stepping motions with is limbs, it is also capable of driving on four wheels. For this purpose, RoboSimian can lower itself onto two active wheels attached to its trunk and two caster wheels on two of its limbs. This allows the robot to drive on even terrain, while still being able to manipulate objects using its other two limbs.

[1]http://www.theroboticschallenge.org/teams

TABLE I

ROBOTIS DYNAMIXEL PRO ACTUATORS USED IN THE LEGS

Joint	Model	Weight	Max. Torque
Hip	H54-200-S500-R	855 g	44.2 Nm
Knee	H54-200-S500-R	855 g	44.2 Nm
Ankle (pitch)	H54-100-S500-R	732 g	24.8 Nm
Ankle (yaw)	H42-20-S300-R	340 g	6.3 Nm
Wheels	2x H42-20-S300-R	340 g	6.3 Nm

On the contrary, DRC-HUBO of the winning team Kaist is basically a humanoid robot and is capable of bipedal walking[2]. Its powerful joint motors are equipped with an air cooling system to dispense heat more efficiently and allow higher payloads. DRC-HUBO can rotate its upper body by 180 degrees which enables it to climb stairs with the knees extending backwards. To improve its mobility, DRC-HUBO is also able to drive over flat terrain using wheels which are attached to its knees and ankles. To switch between walking and driving, DRC-HUBO transforms from the standing position to a kneeling position.

In contrast to DRC-HUBO, CHIMP and RoboSimian, our robot Momaro is capable of driving omnidirectionally, which simplifies navigation in restricted spaces and allows us to make small positional corrections faster. Furthermore, our robot is equipped with six limbs, two of which are exclusively used for manipulation. The use of four legs for locomotion provides a large and flexible support polygon when the robot is performing mobile manipulation tasks.

III. ROBOTIC SYSTEM

Momaro features a unique locomotion design consisting of four legs ending in pairs of steerable wheels (see Figs. 1 and 7). The legs have three pitch joints in hip, knee and ankle, allowing the adjustment of the wheel pair position relative to the trunk in the sagittal plane. Furthermore, the ankle can rotate around the yaw axis and the two wheels can be driven independently. This allows the robot to drive omnidirectionally on suitable terrain, while also stepping over obstacles too high to drive over. Our design goals included a simple, modular lightweight construction. We achieved the goals by driving all joints by Robotis Dynamixel Pro actuators (see Table I), which offer a good torque-to-weight ratio. The leg segments are carbon fiber springs, thus providing passive adaptation to terrain. The forelegs can extend by 40 cm from the lowest to the highest configuration. The hind legs are 15 cm longer to allow the robot to climb steeper inclines.

The wheels are soft foam-filled rubber wheels, which provide ample traction. Their radius of 8 cm and the flexible suspension formed by the carbon fiber springs allows the robot to ignore most obstacles smaller than approximately 5 cm (see Fig. 2).

Momaro is equipped with an anthropomorphic upper body with two 7 DoF arms, enabling it to solve complex manipu-

[2]https://www.youtube.com/watch?v=dcN69YH2NEQ#t=125m

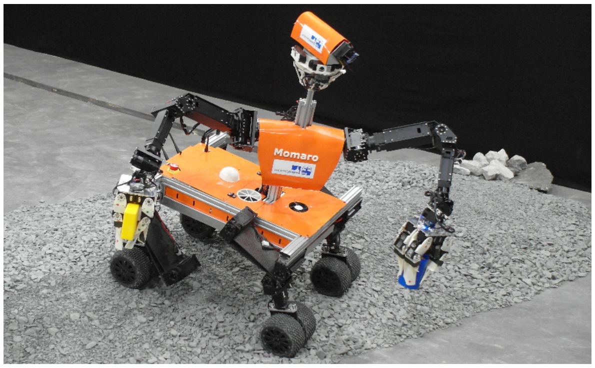

Fig. 2. Momaro successfully participating in the DLR SpaceBot Cup [17] qualification in September 2015.

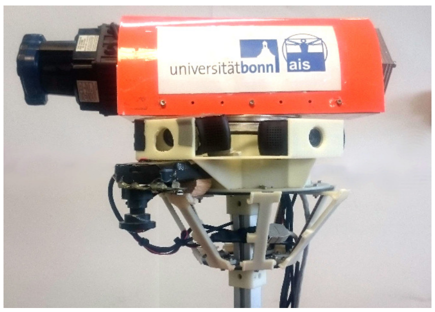

Fig. 3. Sensor head carrying 3D laser scanner, IMU and panoramic cameras

lation tasks. Attached to the arms are two 8 DoF dexterous hands consisting of four fingers with two segments each. The upper body can be rotated around the spine with an additional joint, thus increasing the workspace.

While the legs are used for locomotion as described in the following sections, they also extend the workspace of the robot for manipulation tasks, e.g. by changing the height of the robot or by pitching/rolling the base through one-sided leg length changes.

Momaro's main sensor for environmental perception is a 3D rotating laser scanner on its sensor head (see Fig. 3). It consists of a Robotis Dynamixel MX-64 actuator, which rotates a Hokuyo UTM-30LX-EW laser scanner around the vertical axis. A Pixhawk IMU is mounted close to the laser scanner, which is used for motion compensation during scan aggregation and state estimation. The sensor head also carries four color cameras for operator feedback. Each gripper is also equipped with a camera for configuring and monitoring manipulation tasks. An additional downward-facing wide-angle camera is mounted under the base, which is very useful for monitoring the legs and wheels and possible obstacles below the robot.

Momaro carries an on-board computer with a powerful CPU (Intel Core i7-4790K @ 4 GHz, up to 4.4 GHz) and 32 GB RAM. For communication with the operator and other robots, it is equipped with a NETGEAR Nighthawk AC1900 WiFi router, which allows 2.4 GHz and 5 GHz communication with up to 1300 Mbit/s. Power is supplied to the robot by a replaceable six-cell LiPo battery with 16 Ah

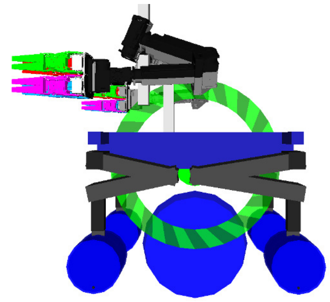

Fig. 4. Graphical user interface for footprint and attitude control. The small blue wheels can be dragged with the mouse to adjust wheel positions. The blue sphere controls all wheels at once, and the green ring can be used to modify the pitch angle of the base.

capacity at 22.2 V nominal voltage, which gives around 2 h run time, depending on the performed tasks.

Performance of the joint actuators is continuously monitored. Feedback information includes measured position, applied torque, and actuator temperature.

The Momaro robot is relatively lightweight (57 kg), which means that it can be carried comfortably by two persons, compared to larger crews and equipment like gantries needed to carry other comparable robots. The legs and upper body can be detached, such that the robot can be transported in standard suitcases.

IV. Omnidirectional Driving

The wheel positions $\mathbf{r}^{(i)}$ relative to the trunk determine the footprint of the robot, but also the orientation of the robot trunk. The operator can manipulate the positions via a graphical user interface (see Fig. 4) either directly for each wheel by dragging it around, moving all wheels together (thus moving the trunk relative to the wheels) or rotating all wheel positions around the trunk origin (thus controlling the trunk orientation).

The operator can control the base movement using a joystick, which generates a velocity command $\mathbf{v} = (v_x, v_y, \omega)$ with horizontal linear velocity $\mathbf{v}$ and rotational velocity ω around the vertical axis. The velocity command is first transformed into the local velocity at each wheel i:

$$\begin{pmatrix} v_x^{(i)} \\ v_y^{(i)} \\ v_z^{(i)} \end{pmatrix} = \begin{pmatrix} v_x \\ v_y \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \omega \end{pmatrix} \times \mathbf{r}^{(i)} + \dot{\mathbf{r}}^{(i)}, \qquad (1)$$

where $\mathbf{r}^{(i)}$ is the current position of wheel i relative to the base. The kinematic velocity component $\dot{\mathbf{r}}^{(i)}$ allows simultaneous leg movement while driving. To actually move in the desired direction, the wheel pair needs to rotate to the yaw angle $\alpha^{(i)} = \text{atan2}(v_y^{(i)}, v_x^{(i)})$.

After all wheels are properly rotated, each wheel moves with linear velocity $||(v_y^{(i)}, v_x^{(i)})^T||$. While driving, the robot continuously adjusts the orientation of the ankle using IMU information to keep the ankle yaw axis vertical and thus retains omnidirectional driving capability.

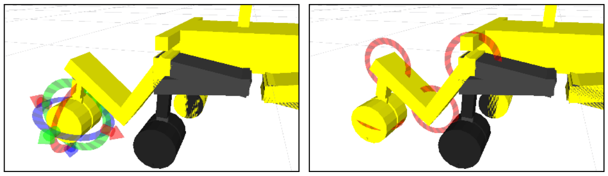

Fig. 5. Graphical User Interface for keyframe editing. The user specifies a Cartesian target pose (left) or a target configuration in joint space (right). The yellow robot model displays the target configuration, while the current robot configuration is shown in black.

V. Motion Design

To support fast and flexible creation of motions by a human designer, we developed a set of motion editing tools. Motions are initially specified using a keyframe editor. At runtime, motions can be loaded, modified to fit the current situation, and finally executed by a player component.

The keyframe editor (see Fig. 5) is based on the standard ROS rviz graphical user interface. It shows the current robot state and the keyframe goal configuration as 3D models. Since the robot has a large number of independent endeffectors and internal joints, keyframes consist of multiple joint group states. For each joint group (e.g. the right arm), the user can specify either a target configuration in joint space, or a target endeffector pose in Cartesian space. Interpolation between the keyframes is controlled by specifying velocity constraints (see below). Furthermore, the user can also control the amount of torque allowed in the motor controllers.

The keyframe player component is responsible for executing designed motions. Keyframes can be adapted to sensory measurements at runtime. Interpolation between the keyframes in either Cartesian or joint space is done online using the freely available Reflexxes library [18], which provides smooth interpolation under acceleration and velocity limits.

During editing and playback, a custom analytical kinematics solver is used to resolve Cartesian poses to joint configurations. Since the legs have four degrees of freedom (excluding the wheels), the solution is always unique as long as it exists.

Besides pre-designing fixed motions, the method can also be used online to teleoperate the robot. In this case, the operator designs single-keyframe motions consisting of one goal configuration, which are then executed by the robot. Operator situational awareness is gained through 3D environment visualization and transmitted camera images. The 3D rotating laser scanner produces a 2D scanline, which is aggregated into a 3D point cloud using the estimated robot motion during the scan. We maintain an egocentric multiresolutional surfel map [19] as the main environmental representation (see Fig. 6), which is transmitted over the communication link. The 3D visualization is displayed in the keyframe editor, providing context for the current and target robot configuration. Note that the arms are usually teleoperated through a different interface using a head-mounted 3D display and magnetic trackers [20].

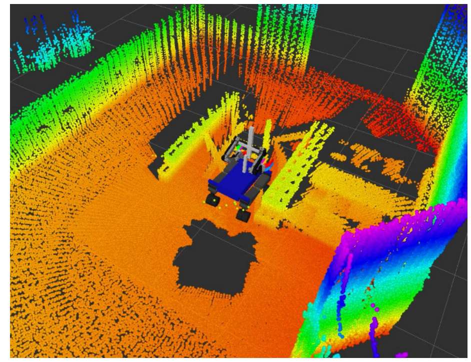

Fig. 6. Point cloud of the egocentric multiresolutional surfel map as viewed by the robot operator during the debris task of the first DRC competition run. The color encodes height.

VI. Semi-Autonomous Stepping

In teleoperated scenarios, a suitable balance between autonomous actions conducted by the robot and operator commands has to be found, due to the many degrees of freedom that need to be controlled simultaneously and due to typically limited communication bandwidth. If the terrain is not known before the robotic mission, the motion design approach described above is not applicable. Our system addresses these scenarios by semi-autonomously executing weight shifting and stepping actions when required and requested by the operator.

The autonomous stepping module uses 3D laser measurements as sensory input. For step parametrization, the egocentric surfel map (see Section V) is projected into a 2.5D height map, shown in Fig. 7.

Gaps in the height map (cells without measurements) are filled with the local minimum if they are inside of a certain distance of valid measurements (10 cm in our experiments). The rationale for using the local minimum is that gaps in the height map are usually caused by occlusions. The high mounting position of the laser on the robot means that low terrain is more likely occluded than high terrain. The local minimum is therefore a good guess of missing terrain height.

After filling gaps in the height map, the height values are filtered using the fast median filter approximation using local histograms of Huang et al. [21]. The filtered height map is now suitable for planning footsteps.

While the operator always retains control of the velocity of the robot base using a joystick, steps can be triggered either automatically or manually. The automatic mode always decides on the wheel pair which most urgently needs stepping for continued base movement with the requested velocity.

To be able to lift a wheel, the robot weight must be shifted away from it. Ideally, the 2D projection of the center of mass (CoM) of the robot should lie in the center of the triangle formed by the other three wheel pairs (see Fig. 7). This ensures static balance of the robot while stepping. Our robot has three ways of achieving this goal, all of which have been used in Fig. 7:

i) moving the base w.r.t. the wheels in sagittal direction,

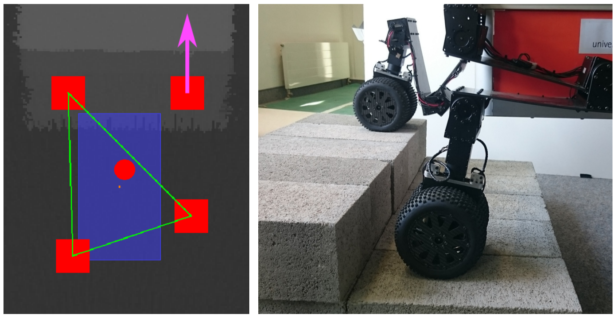

Fig. 7. Left: 2D heightmap of Momaro standing on two steps of a set of stairs in our lab. The robot is in stable configuration to lift the right front leg. Red rectangles: Wheel positions, red circle: COM, blue: robot base, green: support polygon. Right: The right front leg is lifted and placed on the next step.

ii) driving the wheels on ground relative to the base, and
iii) modifying the leg lengths (and thus base orientation).

The balance control behavior ensures static balance using foot motions on the ground (constrained by the detected obstacles) and leg lengths. If it is not possible to move the CoM to a stable position, the system waits for the operator to adjust the base position or orientation to resolve the situation.

The stepping motion itself is a parametrized motion primitive in Cartesian space. The target wheel position is determined in the height map as the first possible foothold after the height difference which is currently stepped over. As soon as the wheel is in the target position, the weight is shifted back using balance control. The operator is then free to continue with either base velocity commands or further steps.

VII. Evaluation

Momaro's locomotion platform has been evaluated in several simulations and lab experiments as well as in the DARPA Robotics Challenge (DRC) Finals in June 2015, and during the qualification runs for the DLR SpacebotCup in September 2015 [17].

An early lab experiment was done to prove that Momaro fulfills the qualification requirements of the DRC. A wooden bar obstacle (20 cm×15.5 cm×154 cm) was placed in front of the robot. For qualification, the robot was required to overcome this obstacle. With a fixed sequence of basic stepping motion primitives, Momaro was able to cleanly step over the obstacle (see Fig. 10). We also showed that Momaro is capable of standing up from the lowest possible configuration (see Fig. 11) to a configuration which allows the robot to drive, mainly using the strong hip actuators, supported by wheel rotation[3].

The DARPA Robotics Challenge consisted of eight tasks, three of which were relevant with respect to locomotion: exiting a car, locomoting over a set of obstacles (either debris on the ground or a special terrain field), and finally climbing a staircase. Additionally, the robot hat to move from one task to the next. Since the overall time limit for all tasks was set at one hour, quick locomotion between the tasks was necessary for solving a large number of tasks. Please note that the Momaro robot design was targeted for more challenging and more numerous locomotion tasks, but DARPA lowered the number and the difficulty of the tasks shortly before the DRC Finals.

In general, the compliance in the legs not only provided passive terrain adaption, but also reduced the required modeling and kinematic precision for many tasks by allowing the robot trunk to move compliantly in response to environment contacts (e.g. while manipulating a wheel with one of the arms). Furthermore, the strength of the base actuators was also used for manipulation, for instance opening the door by positioning the hand under the door handle and then raising the whole robot, thus turning the door handle upwards.

The car task featured a Polaris RANGER XP 900 car (see Fig. 8), which the robot had to drive and exit. Since we did not have access to the car before the competition, we had only a few days at the Fairplex competition venue to determine how to fit the robot into the car and to design an appropriate egress motion. Even though the robot was not designed with this particular task in mind, our base proved to be flexible enough to fit the robot in the car, although the car seat was obviously designed for the biped shape of humans. We extended the accelerator pedal with a small lever to enable Momaro to press it with its front right leg. While other teams opted to seat their robots dangerously close to the side of the car, so that they could exit with a single step, we could place the robot sideways fully into the car and use the robot wheels to slowly slide out of the car, stepping down onto the ground as soon as possible. Also, some teams made extensive modification to the car in order to ease the egressing progress, while we only added a small wooden foothold to the car to decrease the total height which had to be overcome in one step. We designed an egress motion consisting of both driving and stepping components, which made the robot climb backwards out of the co-driver side of the vehicle. Momaro successfully exited the car on the trial day and in the first run of the competition (see Fig. 8). The attempt in the second run failed due to an operator mistake, resulting in an abort of the egress.

Most teams with a legged robot chose to walk over the special terrain field. Instead, we chose to solve the debris task using Momaro's powerful wheels. During the trial and first competition run, the robot simply pushed through the loose obstacles and drove over smaller ones quite fast (see Fig. 12). To maximize stability, we kept the center of mass very low by completely folding the legs. Unfortunately, Momaro got stuck with a wheel in a traverse that was part of the debris during the second competition run. After a longer recovery procedure, the robot still managed to solve the task—although with some failed actuators due to overheating.

Sadly, we could not demonstrate the stairs task during the DRC Finals due to development time constraints and the failure of the system in the second run. However, we were able to show that the robot is capable of climbing stairs directly afterwards in an experiment in our lab (see Fig. 13). To do so, the robot also leverages its base as a ground contact

[3]A video of Momaro solving the qualification tasks is available: `https://www.youtube.com/watch?v=PqTSPD2ftYE`

Fig. 8. Momaro exits the car at the DARPA Robotics Challenge.

point, increasing stability and allowing to use both forelegs simultaneously to lift the base onto the next step[4].

Our team NimbRo Rescue solved seven of the eight DRC tasks and achieved the lowest overall time (34 min) under all DRC teams with seven points[5] — the next team took 48 minutes. This demonstrated the usefulness of having wheels for quick locomotion between the manipulation tasks.

We also used Momaro to participate in the DLR SpaceBot Cup qualification runs in September 2015 (see Fig. 2), where its locomotion system allowed us to easily cross the terrain while performing manipulation tasks with both hands on the floor. The SpaceBot Cup terrain resembles an extraterrestrial surface and is more challenging than the smooth asphalt present at the DRC Finals. The experiments discussed so far show that Momaro's locomotion architecture is capable of solving a wide range of locomotion problems, which partly cannot be solved easily by a purely wheeled system. The hybrid approach ensures that the robot is still able to move quickly and flexibly on sufficiently flat terrain.

The described semi-autonomous stepping controller has been developed in simulation (see Fig. 9) and has successfully and reliably overcome obstacles of various shapes, including series of steps of up to 40° incline. We also conducted initial lab experiments with the real robot using the system (see Fig. 7). Since the DRC environment was mostly static and fixed, stepping motion primitives sufficed for solving the tasks—we did not use the autonomous component during the competition.

VIII. Conclusion

In this paper, we presented the design of our robot Momaro which has a hybrid mobile base combining wheeled and legged locomotion. Additionally, basic control mechanisms for such a system and a semi-autonomous stepping controller were introduced.

The success of the developed robotic system at the DARPA Robotics Challenge and in the lab experiments has demonstrated the feasibility and usefulness of the hybrid design.

Improvements of the design could include an additional roll joint in the hip, which would further increase the flexibility of our robot by enabling it to perform sagittal steps. Remaining issues include overheating actuators due to high torque if the robot stays too long in some specific configurations, e.g. standing on the stairs with one leg lifted for a longer time. This problem arises if the operator is to slow to plan and execute the next motion, which would move the robot in another configuration. Hence, future work will focus on further exploiting the advantages of the design by investigating autonomous planning of hybrid driving and stepping actions, thus allowing true autonomous locomotion over rough terrain and avoiding overheating of the actuators.

[4]Video: `https://www.youtube.com/watch?v=WzQDBRjHRH8`
[5]Video: `https://www.youtube.com/watch?v=NJHSFelPsGc`

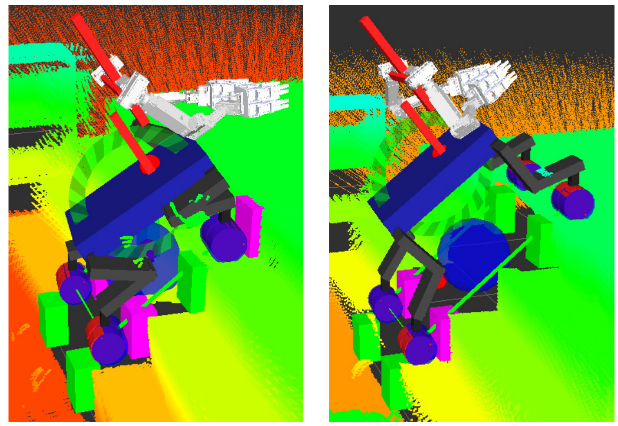

Fig. 9. Momaro climbing stairs in simulation. The purple and green boxes indicate detected obstacles which constrain the wheel motion in forward and backward direction, respectively.

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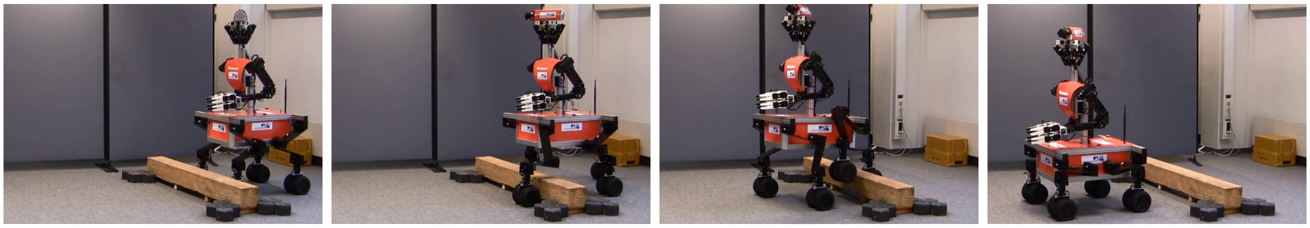

Fig. 10. Momaro steps over a wooden bar obstacle.

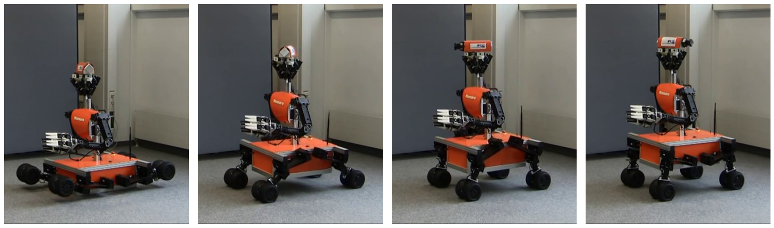

Fig. 11. Momaro stands up from the lowest possible configuration (base on the ground).

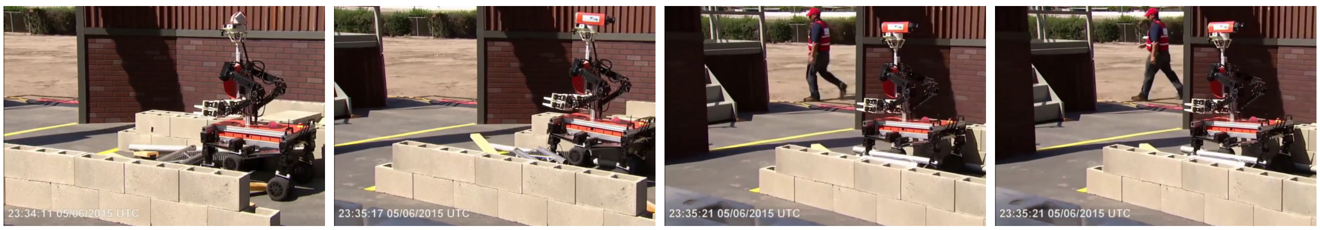

Fig. 12. Momaro pushes through loose debris at the DARPA Robotics Challenge.

Fig. 13. Momaro climbs stairs using a specially designed stair gait.

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