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ALMA - Articulated Locomotion and Manipulation for a Torque-Controllable Robot

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***Abstract*— We present a motion planning and control framework for ALMA, a torque-controlled quadrupedal robot equipped with a six degrees of freedom robotic arm capable of performing dynamic locomotion while executing manipulation tasks. The online motion planning framework, together with a whole-body controller based on a hierarchical optimization algorithm, enable the system to walk, trot and pace while executing tasks such as fixed-position end-effector control, reactive human-robot collaboration and torso posture optimization to increase the arm's kinematic reachability. The torque controllability of the whole system enables the implementation of compliant behavior, allowing a user to safely interact with the robot in a very natural way. We verify our framework on the real robot by performing tasks such as opening a door and carrying a payload together with a human.**

I. INTRODUCTION

Legged robots have great advantages over their wheeled or tracked counterparts. They are capable of traversing challenging terrain and environments which were designed for human use (e.g. steps, stairs, etc.). This is done by modulating the ground reaction forces which allows the robot to retain balance and to enable compliant behavior.

The application of this type of system, which typically includes search and rescue, exploration or inspection tasks, has been limited in the kind of interaction between the machines and their environment. A typical mission for a quadrupedal robot includes mapping, navigating through challenging terrain, and inspecting a scenario which would not be desirable for humans to be [1]. Direct interaction with the environment, however, has been limited to the contacts used for locomotion, with little to no flexibility in the manipulation capabilities. Few robots use their legs for manipulation, however, the possible tasks using the available feet [2] or a gripper tool attached to the feet [3] remain limited and renders simultaneous locomotion and manipulation hard or impossible. Equipping a multi-legged robot with an additional limb which is dedicated to manipulation tasks, greatly extends the possible real-world deployment. Such a robot will be able to carry and move objects, help a human to deliver a payload, open doors and interact with its surroundings in ways which were precluded before.

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Fig. 1. ALMA, a quadrupedal robot equipped with a six DOF robotic arm. The system is fully torque-controlled, which enables compliant behavior.

Various similar solutions have been explored over the past few years [4]. The quadrupedal robot *HyQ* [5] is equipped with a six DOF arm and demonstrates a static walking gait while tracking motions of the arm. The authors propose a controller which takes into account internal and external disturbances created by the manipulator by optimizing for the ground reaction forces.

Impressive results have been achieved by Boston Dynamics' quadrupedal robots *Spot* and *SpotMini*. SpotMini, equipped with a five DOF arm, shows manipulation tasks while walking, e.g., opening a door and carrying a payload. However, so far none of the details on the methods and approaches used to control these robots have been made available. In an older work of Boston Dynamics, the quadrupedal robot *BigDog* [6] demonstrates a throwing maneuver with a robotic arm while trotting in place.

Controlling such a system comes with several challenges. It requires appropriate motion planning and control to enable simultaneous locomotion and manipulation. Such dynamic interaction with the environment through legs and arms of a walking robot requires taking into account the full system dynamics as well as the contact forces at the robot's end-effectors. Optimal contact force distribution for torque-controllable quadrupedal robots was demonstrated in experiments while taking into account equality [7] and inequality [8] constraints. Optimization algorithms to solve the contact force distribution based on the complete system dynamics are shown in [9] and [10]. In these approaches, inequality constraints on the direction and magnitude of the linear contact forces are prescribed, leaving the exact contact force distribution to follow from the other whole-body controller tasks. However, when actively interacting with the environment using an arm (e.g., opening a door), it may be desirable to explicitly prescribe linear contact forces as well as contact torques between the gripper and environment. This increases the complexity of the contact force distribution problem for the entire robot.

In this paper, we present ALMA (Articulated Locomotion and MAnipulation, see Fig.1), a fully torque-controlled mobile quadrupedal manipulation system capable of performing dynamic gaits while executing manipulation tasks. We design a motion planning and control framework which allows the robot to compliantly react to external forces and to maintain balance while executing dynamic locomotion. To the best of our knowledge, this is the first time that such a system is shown performing coordination between dynamic locomotion and manipulation.

II. Model formulation

The model of a walking robot equipped with a robotic arm can be described as a free-floating base B to which limbs are attached. The motion of the entire system can be described with respect to (w.r.t.) a fixed inertial frame I. The position of the Base w.r.t. the inertial frame, expressed in the inertial frame, is written as ${}_I\boldsymbol{r}_{IB} \in \mathbb{R}^3$. The orientation of the Base w.r.t. the inertial frame is parametrized using a Hamiltonian unit quaternion $\boldsymbol{q}_{IB}$. The limb joint angles are stacked in the vector $\boldsymbol{q}_j \in \mathbb{R}^{n_j}$, where $n_j = 18$. We write the generalized coordinate vector $\boldsymbol{q}$ and the generalized velocity vector $\boldsymbol{u}$ as

$$\boldsymbol{q} = \begin{bmatrix} {}_I\boldsymbol{r}_{IB} \\ \boldsymbol{q}_{IB} \\ \boldsymbol{q}_j \end{bmatrix} \in SE(3) \times \mathbb{R}^{n_j}, \quad \boldsymbol{u} = \begin{bmatrix} {}_I\boldsymbol{v}_B \\ {}_B\boldsymbol{\omega}_{IB} \\ \dot{\boldsymbol{q}}_j \end{bmatrix} \in \mathbb{R}^{n_u}, \quad (1)$$

where $n_u = 6 + n_j$, ${}_I\boldsymbol{v}_B \in \mathbb{R}^3$ and ${}_B\boldsymbol{\omega}_{IB} \in \mathbb{R}^3$ are the linear and angular velocity of the Base w.r.t. the inertial frame expressed respectively in the I and B frame. The robot depicted in Fig. 2 has $n_u = 24$, with six DOF coming from the floating base, twelve from the legs, and six from the arm. The equations of motion of mechanical systems which are in contact with the environment can be written as $\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{u}} + \boldsymbol{h}(\boldsymbol{q}, \boldsymbol{u}) = \boldsymbol{S}^T\boldsymbol{\tau} + \boldsymbol{J}_s^T\boldsymbol{\lambda}$, where $\boldsymbol{M}(\boldsymbol{q}) \in \mathbb{R}^{n_u \times n_u}$ is the mass matrix and $\boldsymbol{h}(\boldsymbol{q}, \boldsymbol{u}) \in \mathbb{R}^{n_u}$ is the vector of Coriolis, centrifugal and gravity terms. The selection matrix $\boldsymbol{S} = \begin{bmatrix} \boldsymbol{0}_{n_\tau \times (n_u - n_\tau)} & \mathbb{I}_{n_\tau \times n_\tau} \end{bmatrix}$ selects which DOF are actuated. If all limb joints are actuated, then $n_\tau = n_j$. The vector of constraint forces $\boldsymbol{\lambda}$ is mapped to the joint space torques through the support Jacobian $\boldsymbol{J}_s \in \mathbb{R}^{3n_c \times n_u}$, which is obtained by stacking the constraint Jacobians as $\boldsymbol{J}_s = \begin{bmatrix} \boldsymbol{J}_{C_1}^T & \cdots & \boldsymbol{J}_{C_{n_c}}^T \end{bmatrix}^T$, with n_c the number of limbs in contact.

III. Motion generation

Thanks to the high number of kinematic degrees of freedom of the robot, it is possible to simultaneously and independently control the motion of the floating base and the gripper. The software framework (summarized in Fig.3) allows to send high-level operational space velocity commands in order to drive locomotion in a specified direction, and/or to move the gripper to a desired pose. For locomotion, these velocity commands (together with the actual robot state) are transformed to reference footholds[1] and motion reference trajectories for the robot's whole-body center of mass (COM). This motion generation framework used for ALMA is based on our previous work [11], which describes a reactive online ZMP-based motion planner that enables the execution of dynamic gaits such as a trot, pace and running trot. Continuous replanning of the motion references at a high rate results in a reactive behavior of the robot. This means the robot can cope with unexpected disturbances, such as unmodelled irregularities in the terrain or a push by a human, by updating the motion plans to remain balanced.

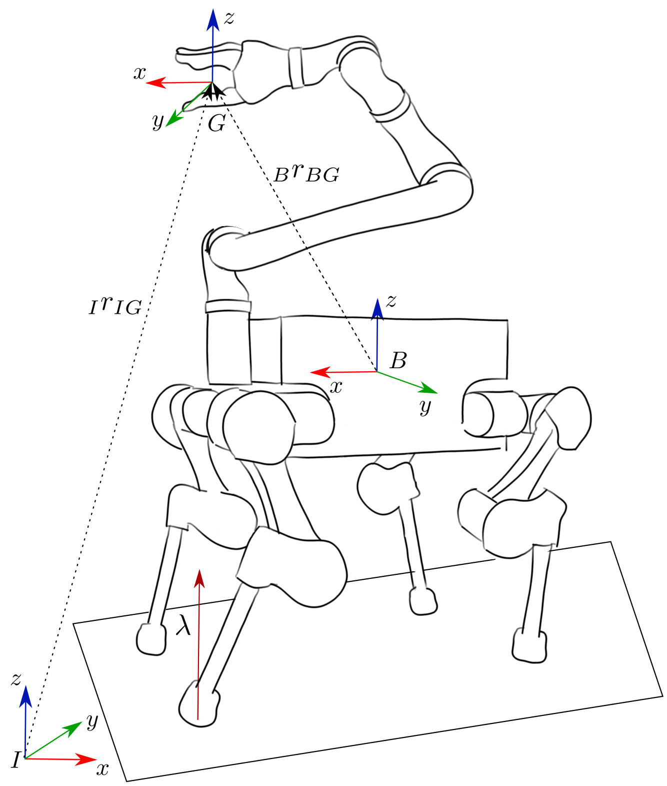

Fig. 2. A sketch of the model used for ALMA. The position of the gripper frame G can be specified either w.r.t. the inertial frame I as ${}_I\boldsymbol{r}_{IG}$ or w.r.t. to floating base frame B as ${}_B\boldsymbol{r}_{BG}$.

A. Gripper Motion References

For the gripper we continuously update a reference pose $\boldsymbol{p}_{IG}^{des}$ and reference twist ${}_I\boldsymbol{w}_{IG}^{des}$ to be tracked by the motion controller. These reference values can come from for example a specific gripper motion planner, or simply from a twist input $\boldsymbol{w}$ coming from a user-operated joystick. In the latter case we update the reference pose as $\boldsymbol{p}_{BG_{k+1}}^{des} = \boldsymbol{p}_{BG}^{des} +^* \Delta t \boldsymbol{w}$, where Δt is the duration of the control loop,

[1] A *foothold* is defined as the desired swing leg contact location.

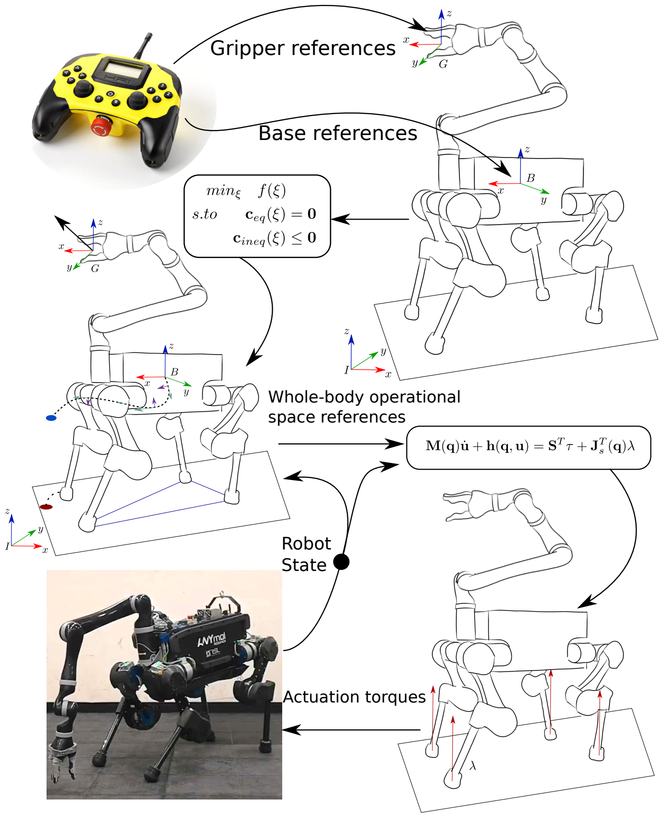

Fig. 3. The planning and control framework described in this paper. High-level velocity references are sent to the floating base or to the gripper. References for the latter are interpreted as velocity updates (w.r.t. the inertial or the floating base frame) for the gripper's desired pose. Velocity references for the base are sent to the online motion generation optimizer which computes COM trajectories. The operational space references are tracked by a whole-body controller algorithm based on hierarchical optimization that generates torque references for all the actuated joints.

and $+^*$ is defined as the vector space addition operator for the translational part of $\boldsymbol{p}_{BG}$ and as $\boxplus$ [12] for the rotational part. The reference twist is updated as ${}_I\boldsymbol{w}_{IG}^{des} = \boldsymbol{w}$.

The motion references for the gripper are expressed and updated either w.r.t. the inertial frame I, or the base frame B. Expressing the reference motion with respect to the inertial frame allows to drive the gripper to a desired place in the world, while the robot is still free to walk, change its posture, and retain balance if an external disturbance is acting on the system. However, in other situations, such as when the robot has to walk to a different location while carrying a payload, it can be desirable to express the reference motion of the gripper w.r.t. the base frame B.

B. Foothold Planning

Our previous implementation of foothold planning was based on the inverted pendulum model [13], and was then included in an online optimization problem [11] which included constraints to avoid the kinematic limits of the legs. In this work, we modify this quadratic programming (QP) problem to plan the footholds w.r.t. the position of the whole-body center of mass instead of the center of the torso. This is crucial since changing the arm configuration can impose a significant shift of the overall COM position.

C. Whole-Body Center of Mass Motion Planning

The desired whole-body COM motion reference trajectory is obtained by solving an online nonlinear optimization [11] which guarantees stable locomotion by constraining the robot's Zero-Moment Point (ZMP) to always lie inside the convex hull of the contact points, i.e., the current and upcoming support polygons. The optimization takes into account different kinds of support polygons (i.e., points, lines, triangles and quadrilaterals). This makes it possible to generate motion plans for any gait that exhibits these support polygons, from a static walk to a running trot with full flight phases and a pronking gait. This motion planner reduces the model of the robot to a single point mass, being the robot's COM. It does therefore not require any adaptations to apply this planner to a quadrupedal robot equipped with one or more additional limbs.

IV. Control

Extending on our previous research [10], [14], we track operational space motion and force references with a whole-body control algorithm which generates torque references for all the controllable joints by using hierarchical inverse dynamics. The controller computes optimal generalized accelerations $\dot{\boldsymbol{u}}$ and contact forces $\boldsymbol{\lambda}$ by solving a cascade of prioritized tasks which specify equality and inequality constraints as $\boldsymbol{A\xi} = \boldsymbol{b}$ and $\boldsymbol{C\xi} \leq \boldsymbol{d}$, where $\boldsymbol{\xi} = \begin{bmatrix}\dot{\boldsymbol{u}}^T & \boldsymbol{\lambda}^T\end{bmatrix}$. The reference torques $\boldsymbol{\tau}_d$ are obtained from the optimal solution $\dot{\boldsymbol{u}}^*$ and $\boldsymbol{\lambda}^*$ as $\boldsymbol{\tau}_d = \boldsymbol{M}(\boldsymbol{q})_j\boldsymbol{u}^* + \boldsymbol{h}_j(\boldsymbol{q}, \boldsymbol{u}) - \boldsymbol{J}_j(\boldsymbol{q})_s^T\boldsymbol{\lambda}^*$, where $\boldsymbol{M}_j$, $\boldsymbol{h}_j$ and $\boldsymbol{J}_j$ are the rows of the mass matrix, nonlinear terms and support Jacobian associated with the dynamics of the directly actuated joints. Table I shows the list of prioritized tasks used throughout our experiments. While the implementation of each task is the same as described in [11], we propose a modified definition of the feet and gripper motion tracking tasks which handle kinematically singular configurations.

We added the control of the added arm into this framework, and present a method for controlling the orientation of the torso in order to increase the arm's kinematic reachability.

A. End-Effector Motion Tracking Task

While executing manipulation tasks, the reference motion for the end-effector can drive the arm to a kinematically singular joint-space configuration. This is likely to happen in the form of full elbow extension when reaching out with the gripper, for example when trying to pick up an object from the ground or a table. The motion tracking task is written as

$$\begin{bmatrix}\boldsymbol{J}_{arm} & \boldsymbol{0}_{3\times n_c}\end{bmatrix}\boldsymbol{\xi} = \ddot{\boldsymbol{x}}_{ref} - \dot{\boldsymbol{J}}_{arm}\boldsymbol{u}, \qquad (2)$$

where $\boldsymbol{J}_{arm} = \partial\boldsymbol{r}_{BE}/\partial\boldsymbol{q}$, with $\boldsymbol{r}_{BE}$ the position of the end-effector w.r.t. the floating base, $\dot{\boldsymbol{J}}_{arm}$ the Jacobian's time derivative and $\ddot{\boldsymbol{x}}_{ref}$ the reference operational space accelerations for the gripper. When the arm is in a kinematically singular configuration, $\boldsymbol{J}_{arm}$ loses rank, which results in this task producing numerically unstable operational space velocity references. This situation is characterized by one of the Jacobian's singular values approaching zero. One way to mitigate this issue is by setting a minimum non-zero value to this singular value and then reconstructing the arm Jacobian $\boldsymbol{J}_{arm}$. This results in the ability to fully extend the arm without running into numerical issues that arise when solving the motion tracking task.

B. Torso Adaptation

A typical task to execute for a mobile manipulator is to reach for and grasp an object. The latter might be, however, out of the kinematic reach (e.g., when on the ground or on a high shelf). This limitation can be addressed by exploiting the kinematic redundancy introduced by the floating base through adaptation of the torso orientation without interfering with the reference positions of the COM (to avoid interfering with the stability criterion in Section III-C) and the gripper (see Fig. 4). For this purpose, we define a desired operational space velocity $\boldsymbol{v}_s^{des}$ for the shoulder (i.e., arm base) which drives the arm to avoid singular positions, and project it to a desired angular velocity for the floating base around its x and y axes as

$$\boldsymbol{\omega}_{B_{xy}}^{des} = \boldsymbol{S}(\boldsymbol{r}_{BS})^{\dagger}\boldsymbol{v}_s^{des}, \quad (3)$$

where $\boldsymbol{S}(\boldsymbol{r}_{BS})^{\dagger}$ denotes the pseudo-inverse of the skew-symmetric matrix which is computed such that $\boldsymbol{S}(\boldsymbol{r}_{BS})\boldsymbol{v}_s^{des} = \boldsymbol{r}_{BS} \times \boldsymbol{v}_s^{des}$, with $\boldsymbol{r}_{BS}$ the position of the mounting point of the arm w.r.t. the base. Subsequently $\boldsymbol{\omega}_{B_z}^{des}$ can be set proportional to $\boldsymbol{\omega}_{B_x}^{des}$ because their relation to the direction of the velocity of the shoulder is identical. The resulting task can be integrated into the task hierarchy as

$$\begin{bmatrix}\boldsymbol{J}_{B_{rp}} & \boldsymbol{0}_{3\times n_c}\end{bmatrix}\boldsymbol{\xi} = k_d(\boldsymbol{\omega}_{B_{xyz}}^{des} - \boldsymbol{\omega}_{B_{xyz}}) - \dot{\boldsymbol{J}}_{B_{rp}}\boldsymbol{u}, \quad (4)$$

where $\boldsymbol{J}_{B_{rp}}$ is the first two rows of the rotational Jacobian of the floating base, k_d is a scalar derivative gain, $\boldsymbol{\omega}_{B_{xyz}}^{des}$ and $\boldsymbol{\omega}_{B_{xyz}}$ are the reference and measured angular velocity respectively, and $\dot{\boldsymbol{J}}_{B_{rp}}$ is the time derivative of $\boldsymbol{J}_{B_{rp}}$.

V. Experiments

Our experiments were conducted on ALMA, which combines ANYmal [15], an accurately torque-controllable quadrupedal robot, and the Jaco[2] [16] six DOF robotic arm from Kinova, developed for use in the field of assistance robotics. The arm is light-weight ($4.4\,\mathrm{kg}$), allows for torque-control of all six actuators, and includes several features for safe interaction with its environment. The control references are generated in a $400\mathrm{Hz}$ control loop which runs on the robot's on-board computer (Intel i7-7600U, 2.7 - 3.5GHz, dual core 64-bit) together with state estimation [17]. We use the open-source Rigid Body Dynamics Library [18] (RBDL), a C++ implementation of the algorithms described in [19], to generate the kinematics and dynamics of the system. The motion generation framework uses a custom sequential quadratic programming (SQP) framework, which iteratively solves a sequence of QP problems by using a custom version of the open-source QuadProg++ [20] library, a C++ implementation of the Goldfarb-Idnani active-set method [21]. The same algorithm is used to numerically solve the cascade of prioritized tasks in the whole-body controller. The following experiments are supported by the video submission[2].

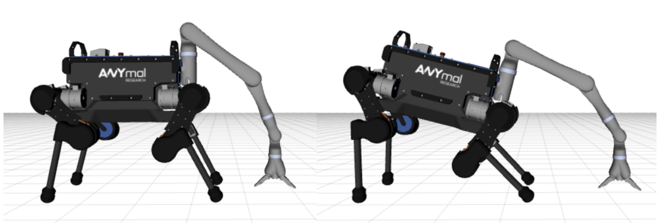

Fig. 4. Reaching on the ground with no base adaptation (left) results in a limited kinematic reach compared to taking into account the configuration of the arm (right). By adapting the orientation of the floating base, the reach in the depicted situation is increased by $15\,\mathrm{cm}$.

TABLE I

THE TASKS USED IN THE EXPERIMENTS. EACH TASK IS ASSOCIATED WITH A PRIORITY (1 IS THE HIGHEST).

Priority	Task
1	Equations of Motion
	Torque limits
	Friction cone and $\boldsymbol{\lambda}$ modulation
2	No contact motion
	Center of Mass linear motion tracking
	Torso angular motion tracking
	Torso orientation adaptation
	Swing foot linear motion tracking
	Gripper spatial motion tracking
	Gripper contact force tracking
3	Contact force minimization

A. End-effector Control

We have tested the coordination of tracking locomotion and end-effector commands by setting a fixed reference for the gripper in the inertial frame while commanding various walking velocities. As depicted in Fig. 5, the robot tracks the gripper's desired location while walking in the desired direction. Thanks to the adapted motion tracking task (see Section III-A), the robot walks until the arm fully extends without suffering from instabilities due to numerical issues when solving the task hierarchy.

B. Compliance and reactive behavior

Based on the reactive behavior described in Section III-C, the system reacts to external disturbances either by producing ground reaction forces which try to counteract the disturbing force or by initiating locomotion to keep balance. Thereby, the proposed approach equally handles disturbances like pushes or pulls acting on the torso, on the end-effector, or any other link of the system. If the external force acts on the end-effector, a very natural following behavior emerges (Fig. 6).

[2]Available at https://youtu.be/XrcLXX4AEWE

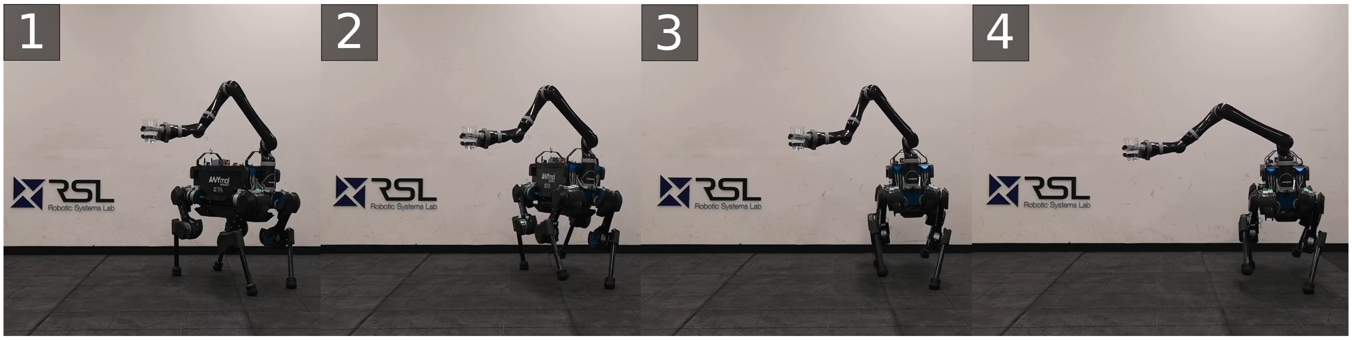

Fig. 5. Having knowledge of the full system dynamics, the controller tracks a fixed end-effector reference while the torso is commanded to walk in a desired direction.

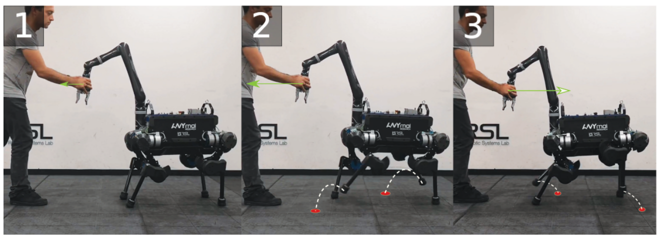

Fig. 6. The robot reacts to external forces acting on the gripper by initiating locomotion to keep balance. Thanks to the reactive behavior introduced by the online motion planner and the compliance defined by the whole-body controller, a user guides the robot to a desired location by acting directly on the system. As depicted in the figure, the planner will generate online footholds references and center of mass trajectories which will retain balance and follow the user's external disturbance. A similar reaction occurs in case of a force applied to the main body or any other link of the system.

C. Human-robot collaboration

As an extension of the experiment described in Section V-C, we have set up a human-robot collaboration scenario (see Fig. 7). The gripper is commanded to pick up a $3.3\,\mathrm{kg}$ box together with a human collaborator. When the box is lifted, the robot reacts to external forces generated at the end-effector. By pulling the box towards himself, the human produces a force on the gripper which initiates locomotion in the direction of the detected force. Thanks to the compliant behavior of the motion planner coupled with the whole-body controller, a collaborative payload delivery task is accomplished.

D. Posture optimization and picking up an object.

Section IV-B describes a task which extends the kinematic reach of the gripper by adapting the angular velocity references of the floating base. Fig. 8 depicts how the base adapts to different configurations of the arm, allowing the robot to easily reach the ground. This behavior is further tested by commanding the robot to pick up an object on the floor (see Fig. 9) and place it on a desk.

E. Opening a door

To illustrate the ability of our whole-body control framework to handle commanded contact forces and torques at the gripper, while accurately controlling the robot's COM motion, we demonstrate the execution of a door opening task while using a trotting gait. To open the door, a desired contact force is commanded at the gripper while constraining the motion of the arm only by commanding zero acceleration of the gripper. The latter task is similar to the "No contact motion" task (Table I) for the stance legs and appropriately constrains the generalized accelerations of the arm joints. A desired contact force at the gripper is computed based on the estimated door angle and error between a desired and actual gripper velocity. Simultaneously the robot is commanded to trot forward to pass through the door. Fig. 10 shows the execution of this task for a spring-loaded door. Because a desired contact force is commanded for the gripper instead of a desired motion, the gripper passively follows the kinematically constrained path prescribed by the door motion, even when contact forces are commanded that are not perfectly tangential to the motion path of the door handle. The whole-body controller task setup, and most specifically the compliance with the high-priority equations of motion task, guarantees a dynamically consistent contact force distribution over the robot's limbs during the execution of this task.

VI. Conclusions and future work

We present results on one of the first fully torque-controllable quadrupedal robots equipped with a robotic arm which is capable of performing dynamic locomotion while execution manipulation tasks. We equipped ANYmal, a torque-controllable quadrupedal robot, with a Jaco^2 robotic arm from Kinova, a six DOF service robotics manipulator. This extends the capabilities of ANYmal to perform manipulation tasks while locomoting, e.g., payload delivery, human-robot collaboration and direct interaction with its surroundings. An online ZMP-based motion planning framework is employed to the new system to enable reactive behavior while executing manipulation tasks. Control references are generated by a whole-body controller which takes into account the dynamics of the whole system, in contrast to other works in this field where the arm is seen as a disturbance to be compensated.

Future work will focus on extending the motion planning framework to take into account the contact locations of the hand for stability. This means that the support polygons will change, and that the ZMP approximation of the system

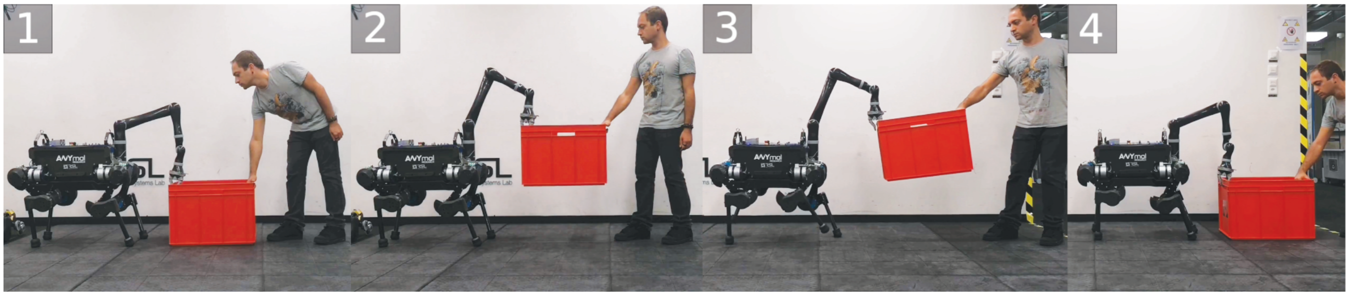

Fig. 7. ALMA carrying a 3.3 kg payload together with a human collaborator. Locomotion is triggered when the force on the gripper in the $x - y$ plane perpendicular to gravity is greater than a user-defined threshold. The online motion planner described in Section III-C computes the required motion reference trajectories for locomotion in the direction of the detected force.

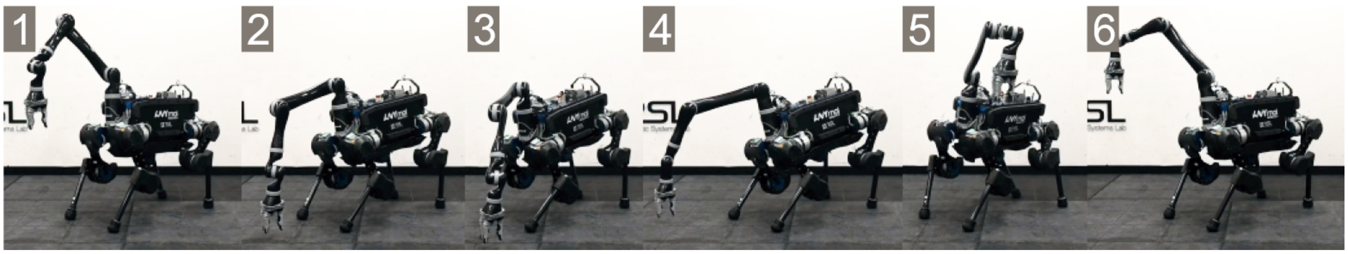

Fig. 8. By setting up an angular velocity reference task for the floating base, the robot adapts its posture to increase the kinematic reach of the gripper. The figure shows the torso adaptation for different end-effector locations.

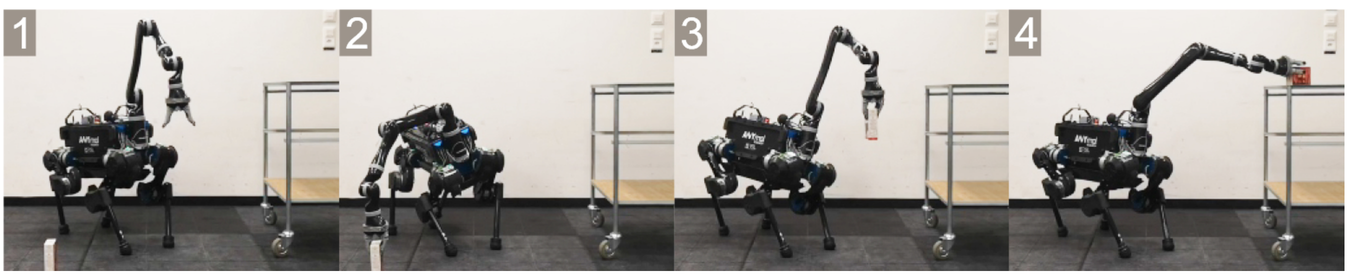

Fig. 9. The system can be controlled to execute manipulation tasks such as picking up an object from the floor and placing it on a desk. The torso adaptation introduced in the whole-body controller helps the robot reach the object both when picking it up and when releasing it.

Fig. 10. Commanding a contact force task instead of a motion task for the gripper allows the robot to open a spring-loaded door without requiring exact knowledge of the door kinematics. Integration of this task in the whole-body controller combined with the COM-based locomotion controller enable the robot to simultaneously perform a trotting gait to pass through the door.

dynamics will be not be valid in the case of non-coplanar contact locations. Trajectory optimization algorithms can be explored which will plan for contact locations for the arm's end-effector. This would allow the robot to hold itself on a rail while walking on stairs.

REFERENCES

[1] C. D. Bellicoso, M. Bjelonic, L. Wellhausen, K. Holtmann, F. Günther, M. Tranzatto, P. Fankhauser, and M. Hutter, "Advances in real-world applications for legged robots," *accepted for Journal of Field Robotics*, 2018.

[2] P. Fankhauser, "Perceptive Locomotion for Legged Robots in Rough Terrain," Ph.D. dissertation, ETH Zurich, 2018.

[3] G. Heppner, T. Buettner, A. Roennau, and R. Dillmann, "Versatile - High Power Griper for a Six Legged Walking Robot," in *Mobile Service Robotics*. WORLD SCIENTIFIC, aug 2014, pp. 461–468. [Online]. Available: http://www.worldscientific.com/doi/abs/10.1142/9789814623353{_}0054

[4] B. U. Rehman, D. G. Calwell, and C. Semini, "Centaur robots - a survey," in *Human-centric Robotics-Proceedings Of The 20th International Conference Clawar 2017*. World Scientific, 2017, pp. 247–258.

[5] B. U. Rehman, M. Focchi, J. Lee, H. Dallali, D. G. Caldwell, and C. Semini, “Towards a multi-legged mobile manipulator,” in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, May 2016, pp. 3618–3624.

[6] Y. Abe, B. Stephens, M. P. Murphy, and A. A. Rizzi, “Dynamic whole-body robotic manipulation,” in *Proc. SPIE 8741, Unmanned Systems Technology*, 2013.

[7] L. Righetti, J. Buchli, M. Mistry, M. Kalakrishnan, and S. Schaal, “Optimal distribution of contact forces with inverse-dynamics control,” *The International Journal of Robotics Research*, vol. 32, no. 3, pp. 280–298, 2013.

[8] M. Hutter, H. Sommer, C. Gehring, M. Hoepflinger, M. Bloesch, and R. Siegwart, “Quadrupedal locomotion using hierarchical operational space control,” *The International Journal of Robotics Research (IJRR)*, vol. 33, no. 8, pp. 1062–1077, may 2014. [Online]. Available: http://dx.doi.org/10.1177/0278364913519834

[9] A. Herzog, N. Rotella, S. Mason, F. Grimminger, S. Schaal, and L. Righetti, “Momentum control with hierarchical inverse dynamics on a torque-controlled humanoid,” *Autonomous Robots*, vol. 40, no. 3, pp. 473–491, 2016.

[10] C. D. Bellicoso, F. Jenelten, P. Fankhauser, C. Gehring, J. Hwangbo, and M. Hutter, “Dynamic Locomotion and Whole-Body Control for Quadrupedal Robots,” in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2017), Vancouver, Canada, September 2428, 2017*. IEEE, 2017.

[11] C. D. Bellicoso, F. Jenelten, C. Gehring, and M. Hutter, “Dynamic locomotion through online nonlinear motion optimization for quadrupedal robots,” *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2261–2268, July 2018.

[12] M. Bloesch, H. Sommer, T. Laidlow, M. Burri, G. Nuetzi, P. Fankhauser, D. Bellicoso, C. Gehring, S. Leutenegger, M. Hutter, and R. Siegwart, “A Primer on the Differential Calculus of 3D Orientations,” jun 2016. [Online]. Available: http://arxiv.org/abs/1606.05285

[13] C. Gehring, S. Coros, M. Hutter, C. D. Bellicoso, H. Heijnen, R. Diethelm, M. Bloesch, P. Fankhauser, J. Hwangbo, M. Hoepflinger, and R. Siegwart, “Practice makes perfect: An optimization-based approach to controlling agile motions for a quadruped robot,” *IEEE Robotics Automation Magazine*, vol. 23, no. 1, pp. 34–43, March 2016.

[14] C. D. Bellicoso, C. Gehring, J. Hwangbo, P. Fankhauser, and M. Hutter, “Perception-less terrain adaptation through whole body control and hierarchical optimization,” in *2016 IEEE-RAS 16th Int. Conf. on Humanoid Robots (Humanoids)*, Nov 2016, pp. 558–564.

[15] M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, P. Fankhauser, M. Bloesch, R. Diethelm, and S. Bachmann, “ANYmal - A Highly Mobile and Dynamic Quadrupedal Robot,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2016.

[16] A. Campeau-Lecours, H. Lamontagne, S. Latour, P. Fauteux, V. Maheu, F. Boucher, C. Deguire, and L.-J. C. L’Ecuyer, “Kinova modular robot arms for service robotics applications,” *Int. J. Robot. Appl. Technol.*, vol. 5, no. 2, pp. 49–71, July 2017. [Online]. Available: https://doi.org/10.4018/IJRAT.2017070104

[17] M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger, and R. Siegwart, “State estimation for legged robots on unstable and slippery terrain,” in *2013 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*. IEEE, nov 2013, pp. 6058–6064. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6697236

[18] Martin Felis, “Rigid Body Dynamics Library,” Available at http://rbdl.bitbucket.org/.

[19] R. Featherstone, *Rigid Body Dynamics Algorithms*. Boston, MA: Springer US, 2008. [Online]. Available: http://link.springer.com/10.1007/978-1-4899-7560-7

[20] Luca Di Gaspero, “QuadProg++,” Available at http://quadprog.sourceforge.net/, 1998.

[21] D. Goldfarb and A. Idnani, “A numerically stable dual method for solving strictly convex quadratic programs,” *Mathematical Programming*, vol. 27, no. 1, pp. 1–33, 1983.