mc-mujoco: Simulating Articulated Robots with FSM Controllers in MuJoCo

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Fig. 1: A screenshot of the mc-mujoco interface with HRP-4CR (left), JVRC1 (middle), HRP-5P (right) humanoid robots, and the Unitree AlienGo quadruped being simulated simultaneously under a QP controller. The native mc-rtc GUI and a new convenience panel are integrated into the same GLFW window eliminating the dependence on external applications. mc-rtc visuals and 3D markers have been deliberately disabled.

Abstract—For safe and reliable deployment of any robot controller on the real hardware platform, it is generally a necessary practice to comprehensively assess the performance of the controller with the specific robot in a realistic simulation environment beforehand. While there exist several software solutions that can provide the core physics engine for this purpose, it is often a cumbersome and error-prone effort to interface the simulation environment with the robot controller being evaluated. The controller may have a complex structure consisting of multiple states and transitions within a finite-state machine (FSM), and may even require user input through a GUI.

In this work, we present mc-mujoco — an open-source software framework that forms an interface between the MuJoCo physics simulator and the mc-rtc robot control framework. We provide implementation details and describe the process for adding support for essentially any new robot. We also demonstrate and publish a sample FSM controller for bipedal locomotion and stable grasping of a rigid object by the HRP-5P humanoid robot in MuJoCo. The code and usage instructions for mc-mujoco, the developed robot modules, and the FSM controller are available online.

I. INTRODUCTION

With the open-sourcing of its source code, DeepMind’s MuJoCo physics engine has become a popular choice of simulation environment in the robotics research community. The library claims to provide computationally efficient simulation without compromising significantly on the accuracy and stability of the simulation \cite{1}, \cite{2}, \cite{3}. Specifically, it offers optimization-based contact dynamics that allow for soft contacts and other constraints, in addition to using a generalized coordinates system. The library offers a C API for interacting with the simulation environment, and the user must rely on this API to read sensor measurements from the simulation state and to apply control signals to the robot actuators, or to control other aspects of the scene like changing model parameters or visualizations.

A powerful yet user-friendly software framework for implementing model-based controllers is provided in mc-rtc - a real-time middleware built on top of the SpaceVecAlg, RB-Dyn and Tasks libraries \cite{1}. mc-rtc has been used extensively to control several humanoids and robot arms using Quadratic Programming (QP) \cite{4} based controllers to perform a diverse variety of demonstrations \cite{5}. It provides a friendlier way to implement complex robot behaviours along with graphical tools for visualizations, user-inputs, logging, and more.

While the C API of MuJoCo provides a deep, low-level access to the simulator’s functionality, there is a need to develop a higher-level interface between mc-rtc and MuJoCo so that developers can reliably and efficiently simulate complex controllers and evaluate the robot’s behavior in a dynamic simulator before deployment on the real hardware. Ideally, such an interface would also allow online user-interaction with the simulation environment to apply externally perturbation to the robot or objects. We develop mc-mujoco to satisfy exactly this requirement (Figure 1). mc-mujoco supports any robot and controller expressed as mc-rtc modules, and

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\textsuperscript{1}https://jrl-umi3218.github.io/mc_rtc/index.html
eliminates the need for the user to directly interact with the low-level MuJoCo library. mc-rtc interface is developed in a transparent manner so that the same controller code used for simulation — running in mc-mujoco — can also be used with the real robot – running in the appropriate interface for a given robot. This greatly simplifies the process of reliably assessing a controller.

Existing interface packages such as mc-openrtm allow mc-rtc to communicate with the OpenRTM middleware [6] used in the HRP robots and Choreonoid simulator [7]. mc-naoqi is an interface developed for the Softback Robotics NAO and Pepper robots [8]. We argue that mc-mujoco provides a higher level of versatility and unique tools compared to the existing solutions along with simulation accuracy and speed due to the underlying MuJoCo physics. Compared to using mc-openrtm, our framework provides more flexibility due to independence from OpenRTM. Moreover, MuJoCo has the ability to simulate joint damping, static friction (both unavailable in Choreonoid) and rotor inertia — important factors for achieving stable and realistic simulations.

To reiterate, we make the following contributions through this work:

- We publish an open-source software framework mc-mujoco that interfaces a popular robot control framework mc-rtc with the MuJoCo physics simulator, and consequently, allows simulation of a wide range of robots with FSM controllers.
- We publish robot description packages for: JVRC1 humanoid robot, the AlienGo quadrupedal robot, and achieve stable simulation in mc-mujoco. We also perform simulations of bipedal locomotion with the HRP-5P and HRP-4CR humanoid robots.
- We develop an FSM controller for the HRP-5P humanoid robot and demonstrate its application for simulation of object grasping and manipulation using our proposed software framework.

II. APPROACH

In this section, we first describe the overall control framework and the key implementation details of mc-mujoco, and then outline the procedure to add support for new robots using description packages. Subsequently, we discuss features for multi-robot simulation and online user interaction using the GUI. An overview of the proposed software architecture is shown in Figure 2.

A. Interface overview

**Actuator modelling and applying control signals.** As it is common to find servo-type actuators driven by a PD control loop in most robots, in mc-mujoco we simulate the same effect by defining a direct-drive torque actuator for each active joint in the XML model. The desired torque at the motor level is computed by a PD control loop and is then sent to these direct-drive actuators where it is scaled up by specified transmission gear ratio by the MuJoCo engine and applied to the joint.

The input to the PD control loop — reference joint positions and velocities — are obtained from the output of mc-rtc computed by double-integration of the desired accelerations predicted by the underlying QP controller.

The execution frequency of the PD controller is decided by the simulation timestep declared in the model XML, usually set to 1 ms. Hence, the PD controller generally runs at 1000 Hz. However, the mc-rtc controller could be running at a lower frequency, and consequently the references to the PD control loop are interpolated from this lower frequency command signal. For model-based humanoid locomotion, the closed-loop balancing controller is generally running at 200 Hz or more.

We also provide support for MuJoCo’s position and velocity actuators. Thus, a PD controlled actuator could also be created by attaching one position and one velocity actuator to the same joint. Lastly, passive joints where no actuator is attached are also supported in mc-mujoco.

**Reading sensor data from the simulation state.** In the opposite direction, feedback data from the simulation environment at each timestep is read and relayed to mc-rtc. This data includes measurements from sensors — such as Inertial Measurement Units (IMUs), force sensors, joint encoders, joint torque sensors — and ground truth values for

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Footnotes:

1. https://github.com/rohanpsingh/mc_mujoco
2. https://github.com/isri-aist/jvrc_mj_description
3. https://github.com/rohanpsingh/aliengo_mj_description
4. https://github.com/rohanpsingh/mjgrasp-fsm-sample-controller
5. https://github.com/rohanpsingh/mc-rtc

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![Fig. 2: Basic outline of the mc-mujoco software framework.](image-url)
position, orientation, linear and angular velocities, and linear and angular accelerations of the floating-base link.

This data is conveyed to mc-rtc which uses it to update state estimators and provide feedback to the controller. The ground truth state of the floating-base link from MuJoCo may be used for debugging purposes and to evaluate accuracy of the state observer pipeline within the simulation environment, as this reading is rarely available on a real robot without using complicated motion capture setups.

Further, we read pixels from all cameras defined in the robot model and render them in a new window to simulate RGB cameras installed on the real robot. The RGB images are also made available to the “DataStore” facility of mc-rtc, explained below, and could be published over ROS in a Virtual Reality (VR) or teleoperation scenario.

**Datastore Calls.** The “Datastore” facility is provided by mc-rtc to share arbitrary C++ objects — including function objects — between states of an FSM or between the interface and the controller. In mc-mujoco, we use this feature to store callbacks for two purposes: (1) read and write PD gains for the servos and (2) reading the 3-channel image matrix from a specified camera. The callbacks may be called from within the controller code or any mc-rtc client with access to the controller’s instance. The datastores for PD gains may be necessary for controllers that use variable gain PD control — where the gains are modified depending on the required robot compliance or stiffness for a specific task. We plan to add support for depth images in a future release.

**B. Robot description**

In the current implementation, any robot that is to be simulated in mc-mujoco must be represented in two structures - (1) the MJCF format for representing the robot in MuJoCo and (2) the robot module for representation in mc-rtc. Environmental objects such as the ground plane or 3D objects for manipulation do not need a robot module representation if they do not need to be considered within the QP loop, say, for obstacle avoidance.

In MuJoCo, the native MJCF format for modelling robots in MuJoCo can be easily derived from the more popular URDF format. MJCF provides a wider range of features and model elements specific to MuJoCo, such as options to select algorithms for contact computations and set parameters that affect the physics simulation. It also allows for loading “assets” such as meshes, height maps, textures and materials, that can later be referenced by other model elements. The MJCF files are generally stored on the disk as XML files (along with meshes for collision and visualization), and are then parsed and compiled into a low-level data structure called mjModel using an internal compiler by MuJoCo.

In mc-rtc. In addition to the above, a robot must be represented as a RobotModule data structure within mc-rtc. The RobotModule structure allows us to define additional information about the robot such as the default joint configuration, collision pairs, names of sensors and devices attached to the robot. Bounds for joint angles, joint velocities and torques can also be defined which could be used by the controller to generate robot motion. Note that such bounds are also defined in the XML model file that are enforced strictly internally by MuJoCo physics. But it is often useful to define additional, more conservative bounds in the RobotModule that could then be added as constraints to the QP in mc-rtc.

With this work, we publicly release the robot description packages for the JVRC1 humanoid robot and the AlienGo quadrupedal robot. While creating the RobotModule class for any robot is a straightforward process, we plan to introduce a feature to automatically generate the robot module from the MuJoCo XML model files. This will further simplify the process of adding support of new robots in mc-mujoco.

**C. User Interaction**

We enable user interaction with the simulation in two ways. Firstly, we allow the user to apply external forces and external torques to any link of the robot (or, in fact, to any object) with the use of mouse interactions. The ability to apply external perturbations is generally useful, for example, to test robustness of control policies for humanoid locomotion or to displace 3D objects in the environment to test the robustness of a reactive grasping algorithm with manipulator arms. Secondly, we develop our own overlay Graphical User Interface (GUI) which allows the user to control several elements of the simulation and visualization, like controlling the simulation speed, rendering of contact points and contact forces, and toggle the visibility of “geomgroups” — generally used to separate visual elements from simulation elements — of the robot model.

More importantly, we integrate the native GUI of mc-rtc within mc-mujoco. This is convenient because it allows the user to interact with the mc-rtc controller and the FSM framework to transition from one state to another, without launching another application or adding dependency on ROS. Using the built-in GUI the user can also tune controller parameters, such as PID tuning of joint servos and visualize live plots from the controller. Further, interactive markers and visual handles published by mc-rtc are rendered in the scene which can be manipulated by the user, say, to set the target position of a robot end-effector controller. This is currently not possible in Choreonoid, which requires launching a separate window RViz - a 3D visualization tool for ROS.

We use the popular DearImGui graphical user interface library for C++ [9] to develop both the GUIs within the mc-mujoco window.

**D. Multi-robot simulation**

Robot-to-robot interactions is a popular area of research and study including topics such as multi-robot planning and cooperation, robot-robot object handover, and more. mc-rtc by itself provides support for multi-robot control by enabling constraints in the QP optimization problem that account for all the loaded robots (for example, by adding appropriate collision constraints, the QP can generate motion that avoids
collision between 2 robots). In mc-mujoco, multiple robots, each with their own controller, can be simulated simply by creating the description files for each robot and then loading them through the mc-rtc controller. mc-mujoco will automatically merge all the robot models into one MJCF model for representation in the MuJoCo scene, while ensuring there is no name clashing. Objects in the environment can also be loaded in the same manner by creating separate MJCF models for each object.

Figure 1 shows four robots being simulated simultaneously while being controlled by a single mc-rtc controller to hold the desired posture. The reference position for any actuated joint of each of the robots can be changed through the GUI panel which will lead the QP to drive the joint to the desired position while respecting kinematic constraints. More tasks such as end-effector tracking can be added to the QP from within the application without relaunching the simulation.

III. GRASPING DEMONSTRATION

MuJoCo has been used widely for simulating object grasping and manipulation using conventional model-based controllers and controllers based on learned policies [10], [11], [12]. The soft constraint model used in the library increases the stability of the simulation while maintaining the realism.

To demonstrate the practicality of our proposed framework, we develop a simple FSM controller using the HRP-5P humanoid robot for a simple demonstration of grasping an object placed on the top of a table. For this demonstration, we choose HRP-5P as the robot platform due to the wide size of its grippers required to grasp the box object, and due to prior knowledge of tuned hyperparameters required for locomotion using the LIPM-Walking controller. The FSM controller includes states for walking from the start position to the edge of the table using the LIPM Walking controller [13], hand retargetting, and opening and closing of grippers to grasp and then lift up the desired object. Figure 3 shows several keyframes of the implemented motion. The robot starts in the “Initial” state where the only task is to hold the current posture, equal to the predefined “half-sitting” stance. The controller then automatically enters the “DemoFSM” where the stabilizer tasks is executed in parallel to all other tasks. “DemoFSM” begins with walking over a predefined footstep plan to reach the table and perform “Standing”. Then, the “GraspStance” state adds a 6D end-effector transform task to place the right hand over the table and near the object. The remainder of the states for opening the gripper, reaching the object, closing and then lifting up the object, are self-explanatory. All state transitions occur automatically according to the completion criteria defined for each state.

Note that, in this particular example, mc-rtc is not aware of the environment object and hence, a collision between the robot and the table is possible. If the table object is added to mc-rtc, the QP solver can be used to compute a collision-free trajectory.

The full demonstration can be seen in the attached video submission. The controller code with installation and usage instruction is made available on GitHub.

IV. CONCLUSION

Through this work, we developed and publicly released mc-mujoco — a framework for simulating essentially any arbitrary robot in the MuJoCo physics simulator with FSM controllers expressed in mc-rtc. mc-rtc is an already existing popular control framework for developing, tuning, evaluating controllers for a wide variety of robots and has been extensively used to control many real platforms.

Similar to other mc-rtc interfaces (like mc-openrtm) mc-mujoco is also developed in a transparent manner, meaning that the same controller code that is used for verification in the simulation, can also be used for real robot deployment using other communication interfaces. This is beneficial for researchers and developers because it reduces the chances for inadvertently introducing bugs, and maintains the validity or authenticity of the simulated behavior.

Elimination of binding dependency to ROS or other third party applications for graphically acquiring user input is another strong feature of our proposed software.
We hope that the release of mc-mujoco will facilitate research within the robotics community for simulating robots and evaluating various controllers. We plan to actively maintain the GitHub repository and introduce new and exciting features in the future.

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