A Whole-Body Software Abstraction layer for Control Design of free-floating Mechanical Systems

Francesco Romano*, Silvio Traversaro*, Daniele Pucci*, Jorhabib Eljaik†, Andrea Del Prete‡, and Francesco Nori*

*iCub Facility Department, Istituto Italiano di Tecnologia, Genova, Italy. Email: name.surname@iit.it
†Institut des Systèmes Intelligents et de Robotique, UPMC Univ. Paris, 06, Paris, France. Email: eljaik@isir.upmc.fr
‡LAAS/CNRS, Toulouse, France. Email: adelpret@laas.fr

Abstract—In this paper, we propose a software abstraction layer to simplify the design and synthesis of whole-body controllers without making any preliminary assumptions on the control law to be implemented. The main advantage of the proposed library is the decoupling of the control software from implementation details, which are related to the robotic platform. Furthermore, the resulting code is more clean and concise than ad-hoc code, as it focuses only on the implementation of the control law. In addition, we present a reference implementation of the abstraction layer together with a Simulink interface to provide support to Model-Driven based development. We also show the implementation of a simple proportional-derivative plus gravity compensation control together with a more complex momentum-based bipedal balance controller.

I. INTRODUCTION

Nowadays, robotics is moving from the original industrial context to more human-like environments. Foreseen applications involve robots with augmented autonomy and physical mobility. Within this novel context, physical interaction influences stability and balance. Consequently, the requirements and tasks that we expect from some platforms are changing as well. Instead of precise positioning tasks confined in cages in industrial assemblies, robots are foreseen to help in everyday-life tasks such as cleaning houses or elderly assistance.

The increase in complexity of robotic systems demands an increase in complexity of the corresponding control software. While ad-hoc solutions can be easy to implement, it is important to consider scalability, flexibility and portability of the developed software. The possibility to use the same software to control more than one platform can be of enormous importance in simplifying the testing, tuning, and deployment of the same controller on different robots.

Whole-body control has received an increased attention by the robotics community because of the possibility it offers to accomplish tasks coordination and to fully take advantage of the robots dynamics in presence of contacts. Indeed, the possibility to specify multiple objectives, even conflicting, at the same time opens the possibility to properly exploit robots for complex scenarios. In particular, citing the definition from the RAS Technical Committee † “Whole-Body Control aims to i) define a small set of simple, low-dimensional rules (e.g., equilibrium, self collision avoidance, etc.) ii) that are sufficient to guarantee the correct execution of any single task, whenever feasible [...], and of simultaneous multiple tasks [...]. iii) exploiting the full capabilities of the entire body of redundant, floating-based robots in compliant multi-contact interaction with the environment”.

In the context of whole-body control the Task function approach [2] has been successfully used. In this method, the control objectives are represented as n-dimensional continuous output functions, called tasks, to be regulated to zero. All the tasks, together with possible constraints are then transformed into a constrained optimization problem. From a software perspective, different implementations exist nowadays, among which the Stack of Task (SoT) [3], OpenSoT [4], ControlIt! [5] and the Instantaneous Task Specification using Constraints (iTaSC) [6]. The above softwares allow the user to specify the objectives and constraints but they solve the control problem internally. A disadvantage is that they force the user to choose a specific task-based approach to obtain the control solution thus denying the control designer the possibility to synthesize different control laws.

In this paper we propose a different approach for the whole-body control of mechanical systems. We deal with the control problem from a more general perspective, without limiting the user to the use of a task-based approach. Indeed, when we consider a generic control system, we usually identify three main building blocks:

- Plant model. If we consider a model-based control system, in this block the information about the plant model given the current plant state are computed.
- Feedback from the plant. This usually implies the possibility to obtain the current state of the controlled plant.
- Actuation. The control system must interact with the plant.

Any control-oriented software library must provide the above features to be of any use. Given the complexity of robotic systems it can be difficult, time consuming and error prone to write the controller directly in a low-level programming language such as C++. Nevertheless the control library must be efficient as it is usually required to have fast control loops. The aforementioned requirements serve as motivation for a model-based driven approach in such control libraries.

In this paper we propose a software abstraction layer which is responsible of decoupling the control software from i) the actual interface used to obtain the state feedback; ii) the actual interface used to command the actuation; iii) the dy-
dynamic software library used to represent the robot dynamical model. Furthermore the proposed library is scalable and easily portable to other robots or different configurations.

This paper is structured as follows. Section II introduces the mathematical formulation of the dynamics of mechanical systems and it shows an example of a simple classic controller. Section III describes the architecture of the proposed whole-body abstraction library and its key elements. A specific implementation is instead presented in Section IV. The controller mathematically introduced in Section II is implemented with the proposed library in Section V. Finally Section VI draws the conclusions.

II. DYNAMICS OF A MECHANICAL SYSTEM

This section introduces the mathematical formulation commonly used in the robotics literature to describe the dynamics of mechanical systems, such as robots. Because a precise formulation of the mathematical problem is out of the scope of the present paper, we refer the interested reader to books on dynamics of mechanical systems [7], [8], [9] and control systems [10], [11] for further readings.

A. Notation

Throughout the section we will use the following definitions:

- I denotes an inertial frame, with its z axis pointing against the gravity.
- 1n ∈ Rn×n is the identity matrix of size n; 0m×n ∈ Rm×n is the zero matrix of size m × n and 0n = 0n×1.
- Given two orientation frames A and B, and vectors of coordinates expressed in these orientation frames, i.e. Ap and Bp, respectively, the rotation matrix ARI is such that
  \[ ARI = ABRB. \]
- We denote with S(x) ∈ R3×3 the skew-symmetric matrix such that S(x)y = x × y, where × denotes the cross product operator in R3.

B. System modelling

We assume that the mechanical model is composed of n + 1 rigid bodies – called links – connected by n joints with one degree of freedom each. In addition, we also assume that the multi-body system is free floating, i.e. none of the links has an a priori constant pose with respect to the inertial frame. This implies that the multi-body system possesses n + 6 degrees of freedom. The configuration space of the multi-body system can then be characterized by the position and the orientation of a frame attached to a robot’s link – called base frame B – and the joint configurations. More precisely, the robot configuration can be represented by the triplet

\[ q = (p_B^I, R_B^I, q_j), \]

where \( (p_B^I, R_B^I) \) denotes the origin and orientation of the base frame expressed in the inertial frame, and \( q_j \) denotes the joint angles.

The velocity of the multi-body system can then be characterized by the triplet

\[ \nu = (\dot{p}_B^I, \dot{R}_B^I, \dot{q}_j), \]

where \( \dot{R}_B = S(\dot{\omega}_B) R_B \) is the angular velocity of the base frame expressed w.r.t. the inertial frame, i.e. \( \dot{R}_B = S(\dot{\omega}_B) R_B \).

We also assume that the robot is interacting with the environment through nc distinct contacts. The application of the Euler-Poincaré formalism [12] Ch. 13.5] to the multi-body system yields the following equations of motion:

\[ M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + G(q) = B\tau + \sum_{k=1}^{n_c} J_{C_k}^T f_k \]

where \( M ∈ R^{n+6×n+6} \) is the mass matrix, \( C ∈ R^{n+6×n+6} \) is the Coriolis matrix and \( G ∈ R^{n+6} \) is the gravity term. \( \tau \) are the internal actuation torques and \( B \) is a selector matrix which depends on the available actuation, e.g. in case all joints are actuated it is equal to \( B = (0_{n×6}, I_n)\top \). \( f_k = [F_k^\top, \mu_k^\top] \top \in R^{6} \), with \( F_k, \mu_k \in R^3 \) respectively the force and corresponding moment of the force, denotes an external wrench applied by the environment on the link of the \( k \)-th contact. The Jacobian \( J_{C_k} = J_{C_k}(q) \) is the map between the robot velocity \( \dot{q} \) and the linear and angular velocity

\[ \tau v_{C_k} := (\dot{p}_{C_k}^I, \dot{\omega}_{C_k}^I) \]

of the frame \( C_k \), i.e.

\[ \tau v_{C_k} = J_{C_k}(q) \dot{q}. \]

C. Control Example

To illustrate the use of the dynamical model presented in Section II-B we present the classic Proportional Derivative (PD) plus Gravity compensation controller as example.

This kind of controller has been usually applied to fully-actuated fixed-base robots. Considering the model presented in Section II-B this means that the base frame position and orientation are constant and known a-priori and thus they are not part of the robot state.

The control objective is the asymptotical stabilization of a desired constant joint configuration \( q_j^d \) or equivalently the asymptotical stabilization to zero of the error

\[ \dot{q}_j := q_j - q_j^d. \]

The choice of the following control action

\[ \tau = G_j(q) - K_p \dot{q}_j - K_d q_j \]

(2)

where \( K_p, K_d ∈ R^{n×n} \) are the positive definite proportional and derivative gain matrices and \( G_j(q) = [0_{n×6}, I_n] G(q) \), satisfy the control objective, i.e. the stabilization to zero of \( \dot{q}_j \), and it can be proved by Lyapunov arguments [7] Sec. 6.5.1].
III. SOFTWARE ARCHITECTURE

We propose a software abstraction layer to simplify creating whole-body controllers for highly redundant mechanical systems. Given the requirements introduced in the previous sections we highlight four main elements that must be present in the library, i.e. Actuators, Sensors, State and Model. The abstraction offered by the library allows one to also easily implement higher-level interfaces such as a Simulink® interface. Figure 1 summarizes the whole software architecture.

Note that the paradigm described by this library does not assume any particular robot operating system or underlining software as this is left to the actual library implementation.

A crucial feature of the proposed abstraction layer is related to the ordering of the information provided from and to the robot. In fact, the elements that directly interface the hardware, i.e. the Actuators, Sensors and State have to represent the information in a robot-dependent suitable way. On the other hand, the Model element usually interfaces with libraries that represent the information with the formalism of Eq. (1). To further complicate the problem, the control software may want to access only a subset of the degrees of freedom modelled by the dynamics library, or provided by the robot. The whole-body abstraction library must thus orchestrate all the various elements to provide a unified interface to the control software.

We now describe in detail the role that each element has in the proposed library.

A. Actuators

The actuators element abstracts the actual control of the robot motors. In particular it exposes the possible motors controllable mode, e.g. position control, velocity control and torque control just to cite the most common. Of course, it also provides the possibility to specify the references for the low level controllers.

B. Sensors

The sensors element is the counterpart of the actuators element. In fact, it abstracts all the sensors available on the robot, usually the readings from encoders, force/torque sensors or accelerometers and it is responsible for providing access to the latest sensor measurements.

C. State

The state element represents all the possible information which can be measured or estimated on the robot. This implies that state encompasses the information provided by the sensor element. Furthermore, it provides additional information which can come from estimation or filtering of the data. For example, if the robot provides only joint position measurements, e.g. coming from the joint encoders, a first and second derivative filter can provide velocity and acceleration measurements. In case this information is provided by the robot itself, no additional processing is required from the interface. It is
important to notice that in both cases the control software using the abstraction library will remain exactly the same.

D. Model

The last element is the model element. It abstracts the kinematic- and dynamic-related information that a controller needs while computing the control law. In general data are represented with the formalism of Eq. (1). Note that a common requirement for a control library is to control only a subset of the degrees of freedom of a robot, e.g. control only the lower body of a legged robot while walking. For this reason, the library must correctly compute the kinematics and dynamics of the whole system, while considering the possibility to expose only a subset of the quantities as requested by the control software.

IV. IMPLEMENTATION

This section describes the current implementation of the whole-body abstraction library conceptually described in Section II. The code has been implemented in C++ because of its diffusion and computational performance while remaining a high-level programming language. The implementation has been divided in two libraries: the wholeBodyInterface [13] and yarpWholeBodyInterface libraries [14].

A. wholeBodyInterface

The wholeBodyInterface is the direct transposition in C++ of the abstract concepts described in Section III. The code has been implemented in C++ because of its diffusion and computational performance while remaining a high-level programming language. The implementation has been divided in two libraries: the wholeBodyInterface [13] and yarpWholeBodyInterface libraries [14].

B. yarpWholeBodyInterface

The yarpWholeBodyInterface is the actual implementation of wholeBodyInterface specifically considering YARP-powered mechanical systems [15]. Regarding the model implementation we choose as kinematic and dynamic library the iDynTree library [16] and information about the kinematic and dynamic model can be loaded from different sources, e.g. a URDF representation.

The actuators and sensors elements directly interact with YARP control boards. Because a robot possesses in general multiple control boards, these two elements are also responsible for mapping the information coming from the control boards to the degrees of freedom selected by the library user.

Note that, because of the dependency on the YARP library, in the current implementation the state element uses YARP data structures, e.g. vectors and matrices, but this dependency can be easily dropped in future implementations.

C. Simulink Interface for Model-Driven Engineering

C++ applications can leverage the advantages of the proposed abstraction layer while keeping full control of the performance of the control software by directly using the provided C++ implementations. On the other hand, coding and testing a complex control system directly in C++ can be prohibitive. For example, even the simple task of monitoring a signal over time can be complex and requires the use of a dedicated library. The use of software to design and simulate dynamical system models greatly helps the design and synthesis of control systems. Domain-specific software for dynamical systems is a specific case of model-driven engineering [17].

We currently implemented the Simulink interface to our proposed whole-body abstraction library, which can be found in [18]. Most of the features accessible in C++ are also accessible to Simulink models. Furthermore, because the connection with the robot or the simulator is handled by the underlying C++ library, the Simulink interface does not require any particular toolbox to command the robot, e.g. Simulink Real Time®.

A further advantage of using Simulink® with respect to the C++ code consists in the possibility to exploit the abundance of toolboxes and Matlab native functions out of the box.

V. EXPERIMENTS

This section presents the implementation of the PD plus gravity compensation controllers briefly described in Section II-C. We also discuss the results of a more complex controller, namely a momentum-based balancing controller which has been implemented with the Simulink interface described in Section IV-C.

A. PD plus Gravity Compensation

This section reports the code for the example presented in Section II-C i.e. the code for the PD plus gravity compensation controller.

Because it is a simple example we show both the C++ code (see Code 1 and 2) and the Simulink model diagram (see Figure 2). Note that, while the Simulink diagram completely represents the controller, the C++ code snippet has been extracted from the main loop function, i.e. the function which runs at every iteration. How the control thread is created and managed depends on the particular system and it is outside the scope of the present paper.

The snippet of code in Code 1 shows how the specific YARP-based implementation is instantiated. In particular, the current implementation needs information about the URDF model representing the kinematic and dynamic information of the robot and the mapping between the model joints and the YARP control boards. This is provided by the object created at line 4 and passed to the interface constructor at line 7. Additionally, the list of controlled joints are passed to the interface at line 19, just before the interface initialization routine is called.

Reading the code in Code 2 it is possible to observe how all the details regarding the specific robot platform are hidden.
by the library. The object robot, in fact, is accessed through its abstract type, as it can be also seen during its instantiation, i.e. in line 7 of Code 1. In lines 4–7 the state of the robot, i.e. \((q_j, \dot{q}_j)\), is read. The feedforward term, corresponding to \(G(q)\) is computed at lines 10–14 where the last parameter is the resulting gravity compensation term. Finally the error and the feedback term necessary to implement Eq. 2 is computed in lines 17–22. Because we did not use any specific mathematical library we explicitly computed the term \(K_p q_j + K_d \dot{q}_j\) in the for loop. Finally, at line 25 we send the torque command to the robot, which we previously setup to be controlled in torque mode.

**Algorithm 1** C++ code snippet for library initialization

```cpp
//Properties.
// - Fill with model URDF path
// - Yarp controlboard mapping
yarp::os::Property wbiProperties = ...;

//create an instance of wbi
wbi::wholeBodyInterface* m_robot =
new yarpWbi::yarpWholeBodyInterface("PD plus gravity",
 wbiProperties);
if (!m_robot) {
 return false;
}

//Create list of controllable joints
wbi::IDList controlledJoints = ...;
m_robot->addJoints(controlledJoints);
if (!m_robot->init()) {
 return false;
}
```

**Algorithm 2** C++ code for PD plus Gravity compensation

```cpp
wbi::Frame w_H_b; //identity + zero vector

//read state
robot->getEstimates(wbi::ESTIMATE_JOINT_POS, positions);
robot->getEstimates(wbi::ESTIMATE_JOINT_VEL, velocities);

//use model to compute feedforward
robot->computeGravityBiasForces(positions, w_H_b, grav, gravityCompensation);

//compute feedback.
for (int i = 0; i < robot->getDoFs(); i++) {
 error(i) = positions(i) - reference(i);
torques(i) = gravityCompensation(i + 6) - kp(i) * error(i) - kd(i) * velocities(i);
}

//send desired torques to the robot
robot->setControlReference(torques);
```

Figure 2 shows the same code implemented directly in Simulink. It is evident how the block-based diagram is clearer with respect to its C++ counterpart. Furthermore, the possibility to add scopes, or dump signal variables directly into Matlab workspace greatly increases its advantages with respect to directly coding in C++.

### B. Momentum-based Balance Control

To show the power of the proposed architecture we present here a second example, i.e. we show the results of a momentum-based balancing controller which has been synthesized directly by using the Simulink interface. Given the complexity of the control problem we do not report here screenshots or code snippets of the Simulink model, but the model can be examined in [19], while the mathematical formulation can be found in [20].

The YouTube video [21] shows the robot performing complex movements by using the controller implemented and running as a Simulink Model. By using the yarpWholeBodyInterface implementation we also leverage the capabilities of the YARP middleware to seamlessly connect to the real or simulated system. In particular the test platform is the iCub humanoid robot [22], endowed with 53 degrees of freedom, 6-axis force/torque sensors and distributed tactile skin. The robot is simulated on the Gazebo simulator [23] by means of Gazebo-YARP plugins [24]. The same demo has also been implemented on a different configuration of the iCub platform [25]. Note that the two robots have a different set of degrees of freedom. Thanks to the flexibility of the library, the controller code remains the same in both scenarios.

We encourage the interested reader to test the controller on the Gazebo Simulator. Instructions on how to run the controller can be found directly in the model repository readme [19].

### VI. Conclusions

In this paper we presented a software abstraction layer to simplify the development of whole-body controllers. While there are already some whole-body control software libraries, they already define the controller structure and leave to the user only the possibility to specify objectives and constraints.

On the other hand the proposed library leaves complete freedom to the control designer by exposing all the information needed. It does not make any assumptions on the controller structure. The whole-body abstraction library presents also the following advantages:

- it decouples the writing of the controller from a particular robot implementation
- it decouples the writing of the controller from a specific dynamic library implementation
- it allows more concise and clear code as it represents uniquely the code needed to implement the mathematical formulation of the controller. All the implementation details are left to the library
- it allows to benchmark the controller on different platforms or with different implementations.
Furthermore, the possibility to expose the functionality at an higher level than C++ facilitates the writing of controllers as the results on the iCub robot clearly prove.

We voluntarily did not consider some aspects as they are out of the scope of the present contribution. Nevertheless they must be taken into account when a controller is implemented and used on the real system. In particular the following details should be considered:

- how are controllers run on the platform? Do they run as threads?
- how are controllers configured and initialized?
- how is communication with other software performed? For example, how are desired values provided to the controller, coming from a planner or higher-level control loop?

By not considering these details in the abstraction library, we render the library portable to different systems. Indeed, the actual control law is not concerned by the previously listed implementation details.

While the more complex demos have been achieved by directly executing the Simulink model connected to the robot, we recognize the need to automatically generate self-contained C++ code. The advantage is twofold. On one side the autogenerated code is in general more optimized than the code directly executed in Simulink, even if less optimized than ad-hoc C++ code. On the other side, this would remove the requirement of having a Simulink installation on the computers controlling the robot.

**Fig. 2.** Simulink model diagram of the PD plus gravity compensation controller for a fixed-base robot

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