

SOFTWARE ENVIRONMENT FOR ROBOT CONTROL SOLUTIONS DESIGN, OPTIMISATION AND TESTING

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Abstract. In the present paper a software environment for the study and verification of robot control solutions is described. Such a tool is based on closed loop modelling and simulation in the integrated ADAMS-Simulink environment. The proposed method is applied to the study and optimization of the control of a prototypical system, constituted by a reconfigurable robot with parallel architecture and by an open PC based controller.
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1. INTRODUCTION

Nowadays, the adoption of advanced development methods and instruments in order to reduce the “time-to-market” of new products is more and more mandatory in many industrial fields. In particular, with reference to advanced machine tools and robots this involves also the necessity to easily and effectively design or reconfigure their control systems [Bianchi *et al.* 2003; Ferretti *et al.* 2002; Pritschow *et al.* 2002]. Such a requirement is even more critical when controllers of non traditional machines - like parallel or hybrid kinematics machines [Carpanzano *et al.* 2003; Dallefrate *et al.* 2002] - are dealt with. Computer aided design tools exploiting modelling and simulation based facilities are today an interesting emerging technology to support the control system design and validation. Nevertheless, their proper and effective use requires still expert control system engineers, as well as the proper usage of modelling and simulation methods and tools. In this work an integrated environment for robot control systems modelling and simulation is presented, and its application to a real case study is discussed. The most critical modelling and simulation tasks are highlighted and the adopted

solutions as well as the obtained results are outlined. Specifically, Simulink™, a toolbox of MATLAB™, is used to model and simulate the control algorithms [URL Simulink], while ADAMS™ is adopted to model and simulate the controlled robot [URL Adams]. Particularly, to verify and to optimise the control algorithms closed loop simulations are performed by interfacing the two considered tools through the Adams-Controls toolbox. In this work the first goal is the synthesis and the study of control algorithms for a reconfigurable hybrid kinematics robotic system – Morpheum – as an application example, the second one is the verification and optimization of control strategies and algorithms through an integrated simulation environment. The studied control solutions have been also successively implemented and validated on the PC-based controller of the considered machine improving its performance [Carpanzano *et al.* 2004].

2. DESCRIPTION OF THE EXPERIMENTAL SET-UP

The proposed techniques and tools have been investigated with reference to the control of a

reconfigurable hybrid robotic system – Morpheum: Modular Reconfigurable Parallel Upgradeable Machine – realized at ITIA-CNR (Figure 1).



Fig. 1 Morpheum: reconfigurable parallel kinematics robot with four d.o.f.

This robot combines a powerful modular and reconfigurable mechanic structure with an elevated dynamic and variable cargo capacity to answer at the continuous alteration of production requirements. In particular, the mechanic re-configurability of the robot, which can work with a variable number of degrees of freedom - from 2 to 6 - implies also the necessity of a reconfigurable control system. The considered robot is controlled by an innovative control system developed at ITIA-CNR too. Such a control system is realized by two personal computers: the first one is based on a non real time Windows operative system, for less critical tasks like interfaces towards the operator (HMI) and the plant; while the second one is based on a real time QNX operative system for critical motion control tasks [Negri 2001].

3. MODELLING IN THE ADAMS-SIMULINK ENVIRONMENT

In this work the ADAMS tool has been exploited to describe the robotic system, while the Matlab-Simulink tool has been adopted to represent the control system. Such tools have been integrated by means of the ADAMS Controls toolbox. In particular, the robot ADAMS dynamic model has been derived by a Unigraphics static model, as illustrated in figure 4, where also the models parameters and hypothesis are reported. The rigid UG-Model has been modified in the ADAMS environment, by introducing flexible legs, and in the Simulink environment by reproducing the Friction and Ripple (Figure 2) contributions defined directly by means of experiments on the Morpheum robot.

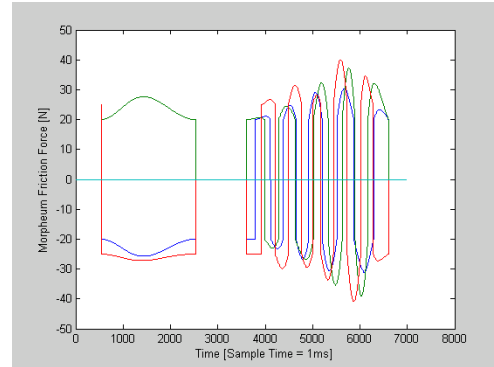
In particular, the most critical aspect of the work concerned the identification of the Friction and Ripple force analytic expressions and parameters by monitoring the Robot movements. The implemented Friction and Ripple forces are shown in equation 1; specifically, in this work two consecutive trajectories, one linear and one circular, have been chosen.

$$F_{\mu} = a_0 * \text{sign}(v) + a_1 * v + a_2 * \text{sign}(v) * v^2$$

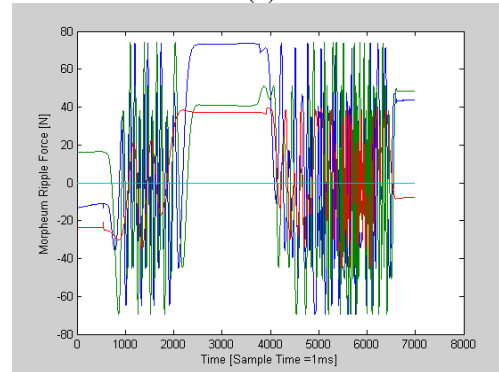
$$F_R = \sum_{N=0}^8 a_N \cos(N * w * p) + \sum_{N=0}^8 b_N \sin(N * w * p)$$

with v : joint velocity
 p : joint position

Friction and Ripple Force Equations. (1)



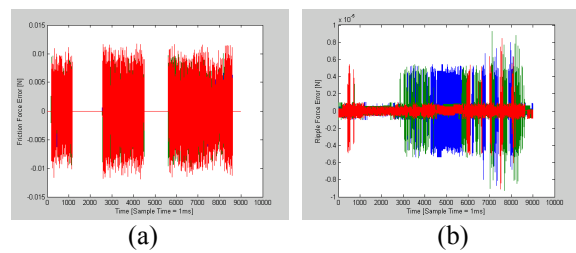
(a)



(b)

Fig. 2 Friction (a) and Ripple Force (b) implemented on Morpheum Controller. Colours: blue – first leg, green – second leg, red – third leg.

The differences between the Friction and the Ripple laws implemented on the Morpheum Controller and the ones implemented in the Simulation Environment are shown in figure 3: it may be noticed that the error absolute value is less than 10mN for the Friction Force and less than 10 μ N for the Ripple Force.



(a)

(b)

Fig. 3 Differences between Friction (a) and Ripple (b) laws implemented in the Morpheum Controller and in the Simulink Environment. Colours: blue – first leg, green – second leg, red – third leg.

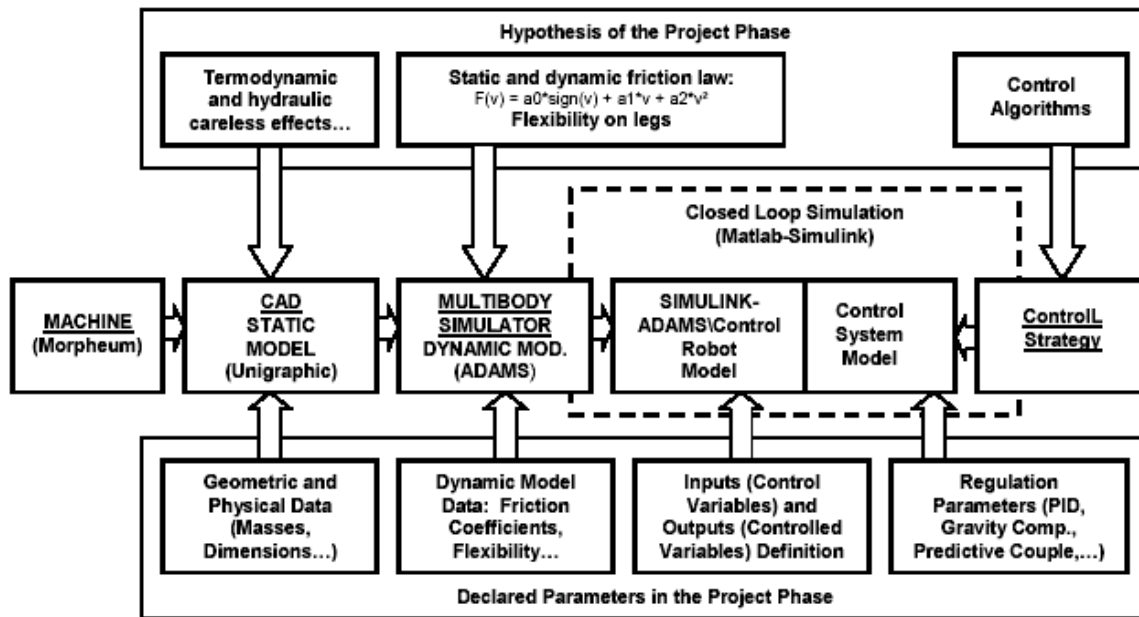


Fig. 4 Closed loop simulation environment.

The Simulink scheme for the integrated simulation of the machine and of its control is shown in figure 5. In particular, in the scheme it is possible to distinguish the following main parts:

- trajectory generation for the end-effector in the Cartesian Space (part 1);
- kinematics transformations: inverse (part 2) and direct (part 5);
- axes control (part 3);
- ADAMS robot model (part 4).

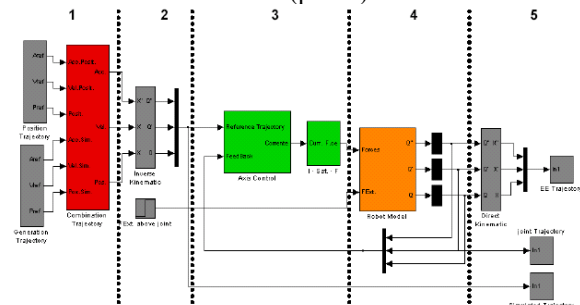


Fig. 5 Simulink scheme for the closed loop simulations.

Figure 7 shows the Simulink blocks defined for trajectory generation. Examples of trajectories generated in the 3D Cartesian Space are reported in figure 6. In particular two different motion laws have been implemented: one law with trapezoidal velocity profile and one with sinusoidal velocity profile.

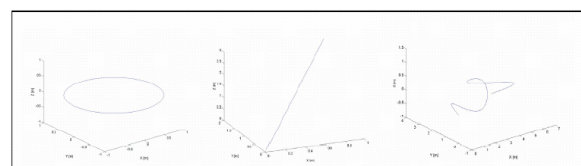


Fig. 6 Examples of trajectories for the end-effector.

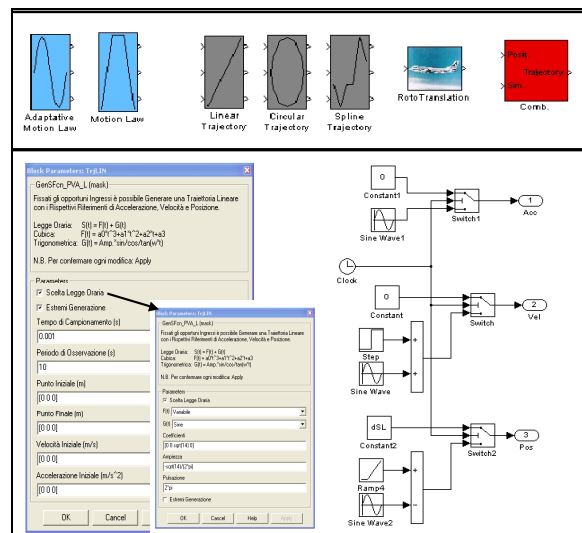
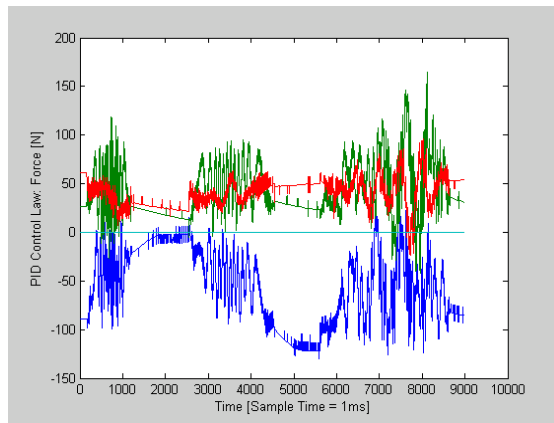


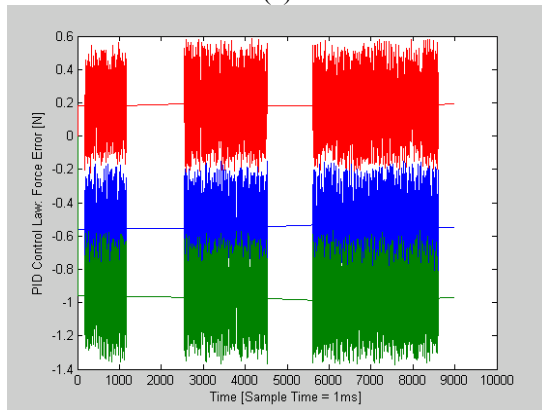
Fig. 7 Trajectory generation blocks.

When the generation time is not an integer multiple of the sample time, these motion laws are able to adapt the generation time in reference to the trajectory, the maximum velocity and acceleration. Different blocks have been implemented in the Simulink environment to model the different studied control strategies; in particular, both traditional (PID, P-PI, P-P-PI) and innovative (sliding mode, gravity compensation,...) control schemes have been considered.

The PID block has been implemented reproducing Morpheus's control law as well as all other algorithms, i.e. Friction, Ripple and Force Compensations. In particular the difference between PID law implemented on the real machine and the PID Simulink block is shown in figure 8(b): the module is less than 0.5N.



(a)



(b)

Fig. 8 PID Control law: Morpheum PID Force (a); difference between Morpheum PID Force and PID Simulink block Force (b). Colours: blue – first leg, green – second leg, red – third leg.

To transform acceleration, velocity and position references of the Cartesian Space to acceleration, velocity and position references of the Joint Space and vice-versa the kinematics direct and inverse transformations have been implemented in Matlab as shown in figure 9.

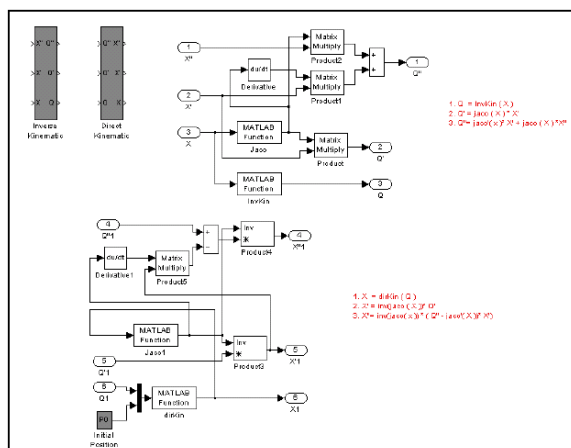


Fig. 9 Simulation scheme for the inverse and direct kinematics transformations.

To realize an accurate model of the robot and to include it in the global Simulink scheme it has been first necessary to import a rigid model from the

Unigraphics environment to ADAMS. Then the Simulink block for closed loop simulations has been generated from the ADAMS model by means of the ADAMS controls toolbox.

Thanks to the Friction and Ripple force model, the Morpheum Simulink block includes not only the contribution of ADAMS block but also the Friction and Ripple effects, so the complete model is shown in figure 10.

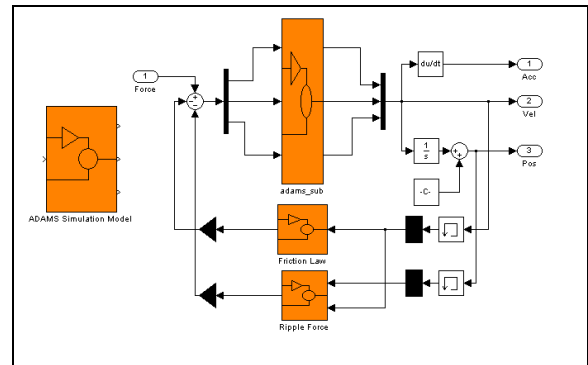
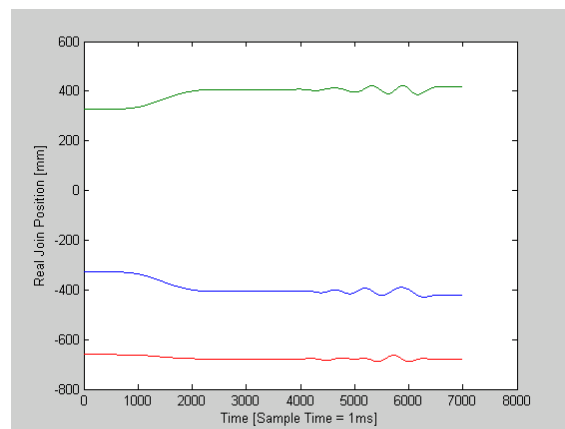


Fig. 10 Morpheum Model in ADAMS-Simulink environment.

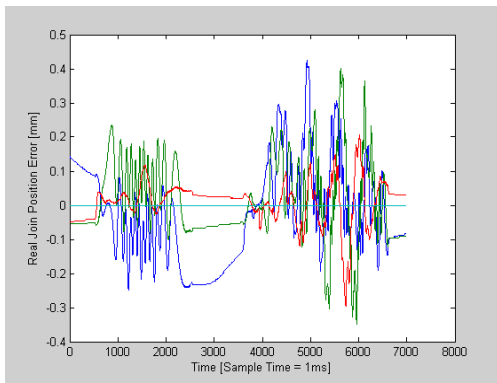
4. SIMULATION AND EXPERIMENTAL VALIDATION RESULTS

The defined simulation environment has been validated according to a particular trajectory tested on the real robotic system. In particular, the CN trajectory corresponds to a sequence of a linear and a circular end-effector movement from the initial point $P_0 = [0, -538.15, 129.52]$ mm.

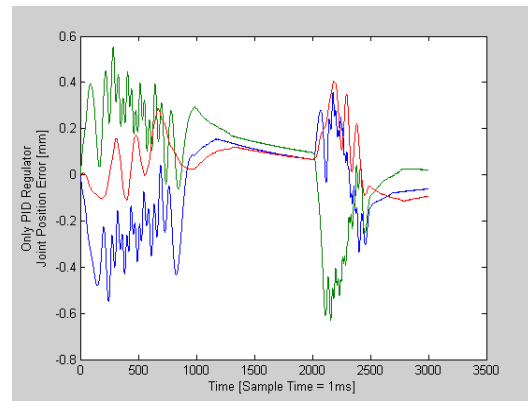
In figure 11 the trajectories generated by the CNC in the joint space are reported (a), as well as the respective real joints position errors (b) and simulated joints position errors (c).



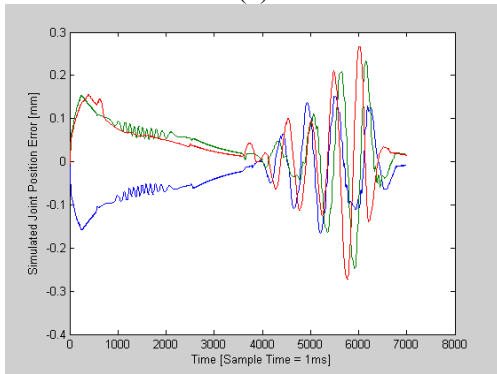
(a)



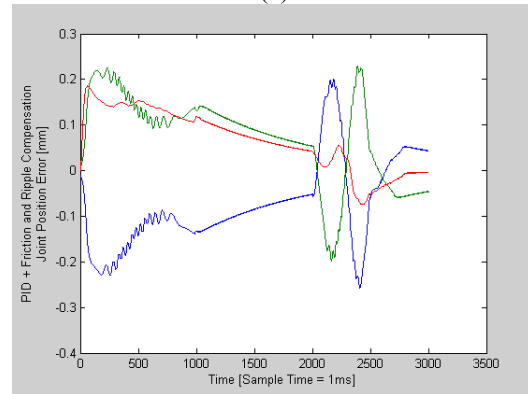
(b)



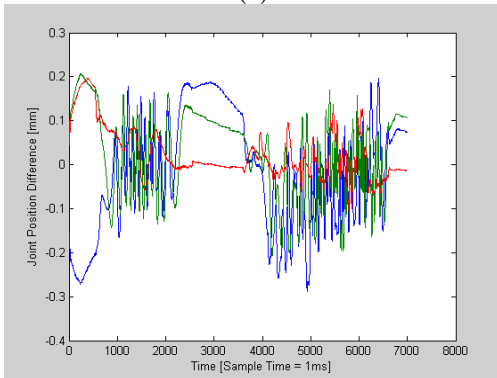
(c)



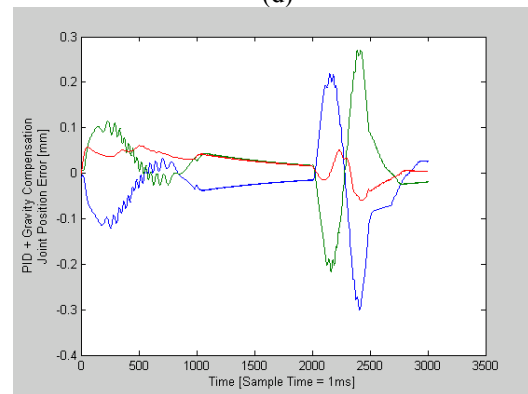
(c)



(d)



(d)

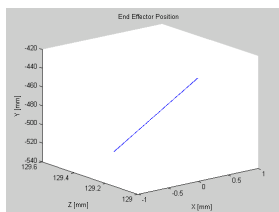


(e)

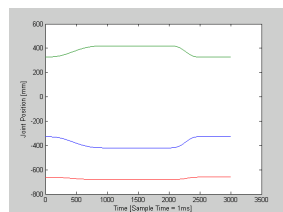
Fig. 11: Validation of the model: trajectory generated in the joints space (a); real position errors of joints (b); simulated position errors of joints (c); difference between real and simulated position of joints (d). Colours: blue – first leg, green – second leg, red – third leg.

It may be noticed that the difference between Real joint position errors and Simulated joint position errors (Figure 11.d) is less than 0.3mm, that is less than the maximum position error.

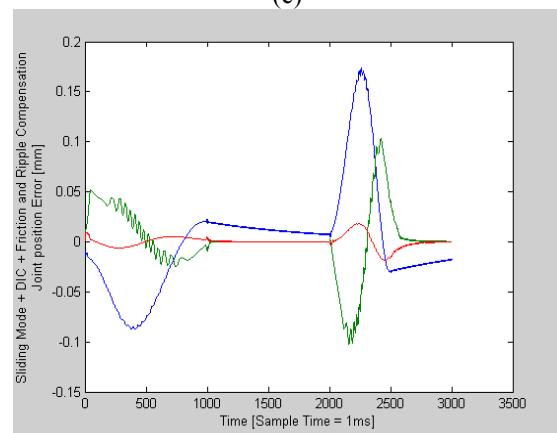
Once the reliability of the simulation environment has been proven, different control strategies have been studied by means of closed loop simulations.



(a)



(b)



(f)

Fig. 12 End-Effector (a) and Joint Position (b); Error for: a simple PID regulator (c); a PID with Friction and Ripple Compensation (d); a PID with Friction, Ripple and Gravity Feed-Forward Compensation (e); a Sliding Mode Control with

Discontinuous Integral Control, Friction and Ripple Compensation (f). Colours: blue – fist leg, green – second leg, red – third leg.

Through the ADAMS-Simulink environment the control strategies have been optimized on the PC-Based Robot Controller. About the same trajectory profile, in figure 12 the performance of a simple PID regulator, a PID regulator with gravity feed-forward compensation, a sliding mode control with the discontinuous integral control are reported.

In particular by introducing Friction and Ripple Compensation it is possible to note a better behaviour of the Joint position error.

As for the gravity compensation scheme a solution is proposed based on a “Forward Compensation” (Figure 13): in this case computational errors of the kinematics direct transformation can be neglected since the gravity compensation is calculated through the reference End Effector position.

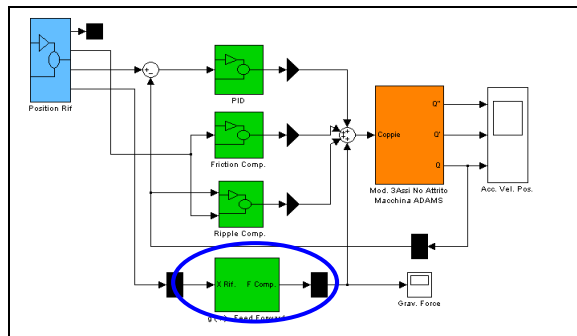


Fig. 13 Forward Gravity Compensation Simulink scheme.

Finally figure 12.f shows the joint position errors with the Sliding Mode and Discontinuous Integral control. The contribution of DIC allows to minimize the oscillations of the control law relative to the sign of the sliding surface. By optimizing the control's parameter it is possible to reduce the error range.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The ADAMS-Simulink environment has been exploited to study motion control solutions by means of integrated mechatronics simulations. Obtained results prove the reliability of the approach and of the tools used. The investigated control strategies and the obtained simulation and experimental results have been addressed, as well as the defined software environment for motion control solutions design and testing. In particular the analytic expression of the Friction and the Ripple forces have been implemented and the Morpheum control strategies and parameters have been optimized.

On going research activities regard the study of a mechatronic modelling and simulation environment

integrating ADAMS (for mechanical components), Dymola (for electrical components) and Simulink (for control strategies).

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URL Adams: www.adams.com

URL Simulink: www.mathworks.com