Internship Report

Elias Aoun Durand
ENSTA Bretagne - UFRJ

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Abstract

This internship report presents the work done during my three months internship in the Laboratory of Robotics of the Federal University of Rio de Janeiro (UFRJ) under Pf. Romano's supervision, where I worked on an application for the Stewart Gough Platform (SGP). The current trend is to build bigger containers ships, but the high cost of the port infrastructure that comes with it is not affordable by every country. This problematic leads to a new kind of scenario where containers ships are discharge offshore instead of in deep-sea port. This report deals with the testing of such offshore discharge via the use of an SGP to simulate the ocean conditions. Here, the platform is used to simulate the movement of a ship under ocean waves conditions.

Ce rapport de stage présente le travail réalisé durant le stage de 3 mois effectué au sein du Laboratoire de Robotique de l'Université fédérale de Rio de Janeiro sous la supervision du Pf. Romano, où j'ai étudié une application au domaine maritime de la plateforme Gough-Stewart. La tendance actuelle est à la construction de porte-conteneurs toujours plus grands, mais le coût très élevé de la construction d'infrastructures portuaires associées n'est pas accessible à tous les pays. Cette problématique amène à un nouveau genre de scénario dans lequel les porte-conteneurs sont déchargés en mer sur des bateaux de plus petite taille plutôt que dans des ports en eaux profondes. Ce rapport traite du test de tel scénario via l'utilisation de SGP pour simuler des conditions océaniques. La plateforme est utilisée pour simuler le mouvement d'un navire en mer.

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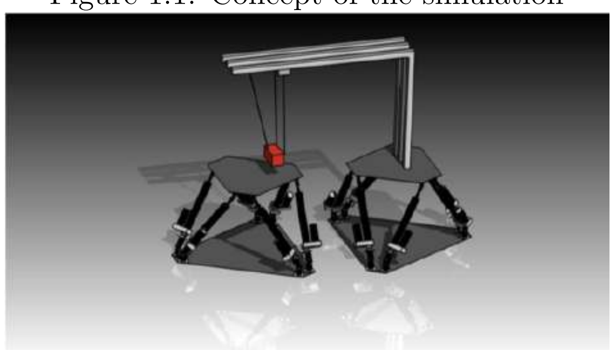


My internship took place in Rio de Janeiro between June and September of 2018 under the supervision of Pf. Romano. I worked in the Laboratory situated in the main campus of the University. This laboratory is part of the COPPE institute of the UFRJ which is the largest Latin post-graduation and research engineering institute.

The Stewart Gough Platform (SGP) is a parallel manipulator which consists of a fixed platform and a moving platform linked together by 6 prismatic joints. The prismatic joints are actuated by servo motors and their lengths are measured by potentiometers. The moving platform has 6 degrees of freedom and can therefore be used for various applications, from surgical tools to flight simulators.

The current application is the simulation of the orientation and position of a ship under different oceanic conditions in a ship-crane interaction. The objective is to place two platforms next to each other and to displace payloads from one to the other using a crane placed on one of the two platforms.

1.2 Objectives and Issues

In 2017, 90 percent of all goods traded in the world passed by the sea. With an average of 3 percent growth per year for 40 years, the world seaborne trade seems to remain the principal way to trade goods in the future. Furthermore, containers ship represents 10 percent of all ships in the world and carried 10 billion tons in 2016 and the trend is actually to build larger boats to increase the capacity of the overall maritime transport system.

In this context, optimizing the tools of this industry is crucial for a more coherent and sustainable future.

With the increase of the size of the ships comes the increase of high depth water ports to welcome those ships. But not all countries can invest or has the possibility to construct such ports. This problematic leads to the possibility of a new way to unload goods without the need of high depth ports: trans-boarding containers from one giant ship to a smaller one at sea, and then unload the smaller boat in smaller ports. In consequences, one of the ship would be equipped with a system that could safely take care of this task. Before my internship, this subject had been studied in a Ph. D. Thesis by Ivanovich Lache Salcedo in 2012 [1]. It is in this scope that my internship took place. The main objective of my internship was to simulate this scenario of trans-boarding using two SGP as boats. More precisely, I had to program the platforms in order to reproduce oceanic conditions such that the crane positioned on one of the SGP could be tested.

1.3 Economical Analysis

Even though the UFRJ has the world's largest water tank for naval engineering studies, the economical context of Brazil has an influence on the investments and facilities in the University. In the past 4 years, the budget of the UFRJ dropped by 10 percent to 388 million reais (around 80 million euros) with a deficit of 160 million reais (around 33 million euros).

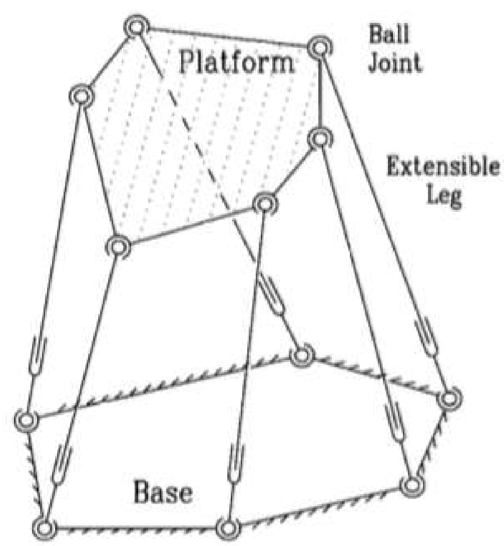
1.4 Personal Organization

During my internship I organized myself in three periods. First I reviewed the state of the art concerning similar applications for an SGP along with a general study of the SGP, its controlability and oceanic wave simulation. Then I programmed the command of the SGP on LabView, integrating into it the desired trajectory composed with the oceanic wave equations. Lastly, I simulated the command using a Matlab-Simulink modelization of the SGP before attempting to implement it on the real one at my disposal in the laboratory.

Chapter 2

Stewart Gough Platform used as a stochastic wave generator in a ship crane interaction

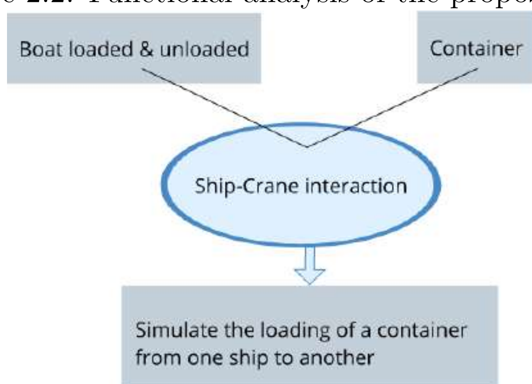
Figure 2.1: A kinematic diagram of a Stewart-Gough Platform



2.1 State of the art of the proposed application

2.1.1 Ship-crane interaction scenario

Figure 2.2: Functional analysis of the proposed scenario

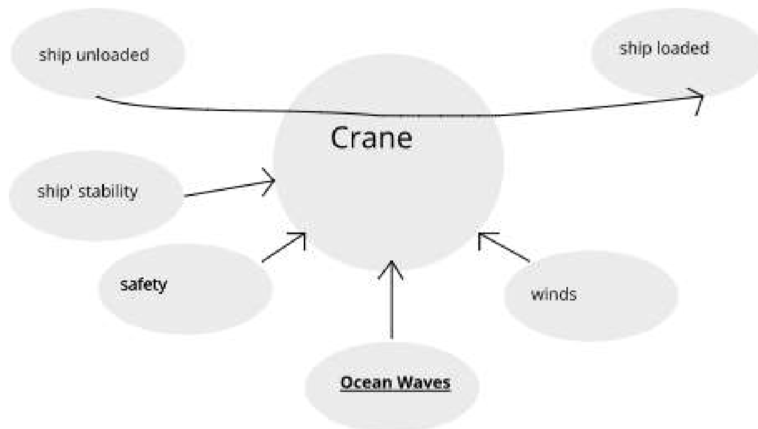


Nowadays, ship-to-ship interactions at sea are mainly used to transfer oil or liquefied gas and other petroleum products. But for other purposes, the ship-to-ship transfer that exist are either direct or indirect: a third ship is needed, (it could also be be an helicopter). Here, the proposed scenario involves two ships with one carrying a crane which can load and unload, safely, containers while they compensate the wave-induced perturbations of the ship's position.Different exterior elements would have an prominent influence on the interaction : the wind, the waves, the stability of the ships, the safety of the equipment and of the staff.

2.1.2 General aspects of ocean wave modeling

The modelization of ocean waves focuses today around three main topics: input by wind, nonlinear interactions, dissipation in deep water. The current state of the art suggests a good understanding of the above principles as can be observed with the accuracy of the operational wave model used by the European Centre for Medium Range Weather Forecast with a 4 percent

Figure 2.3: External elements influencing the interaction



global error. But the models are not perfectly accurate and still rely on empirical assumptions. Some extreme conditions are still not well understood and reproduced by modelization. The spectral linear hypothesis which is the superposition of sinusoidal components does not reflect accurately the complexity of the observed phenomena. An other problem is the practical difficulty to implement nonlinear models of interactions. This wide and complex field of research extends far beyond the current application and I tried to reduce the scope to some basic features that would already be a good approximation of ocean conditions for such application. Considering the previous scenario (boats at rest and calm sea) I listed the minimum features that I thought would be essential.

So I listed what we want in a model of stochastic oceanic waves for the current application. The model should:

- generate realistic motion
- adapt to different wind conditions
- be easy to compute (in terms of basic operations)
- not be completely deterministic

We consider that the observation of the modelized waves are made at the origin of the reference frame.

2.1.3 Stewart platform used as ocean wave generators

The closest project that I found is a Master's Thesis by Magnus B. Kjelland of the Agder University in Norway [10], in which he designed and modelized a compensation sytem for an hydraulic manipulator. The author suggests that the SGP could be used as a wave generator producing realistic motion using an accurate wave spectrum of the North Sea for instance. More generally, I could find examples of heave compensation using the SGP, [7], [10], such as the Ampelmann's Heaved Compensated Walkway in the figure 2.3.

Figure 2.4: the Ampelmann's Heaved Compensated Walkway

2.2 Modelization of Ship Motion in Stochastic Oceanic Waves

2.2.1 Stochastic Wave Model

Before attempting to modelized oceanic waves with a stochastic approach, I tried a deterministic modelization. This modelization is much easier to implement and partially filled the previous qualities reacquired for the current application. This approach is extracted from the article of Alain Fournier and William T. Reeves 'A simple model of ocean waves' [2]. A particle on the free surface of the water is assumed to have a trochoid movement, a generalization of a cycloid. We can then use the following equations :

$$\begin{cases} x = x_0 + rsin(\kappa x_0 - \omega t) \\ z = z_0 - rcos(\kappa x_0 - \omega t) \end{cases} \tag{2.1}$$

where x_0, y_0, z_0 is the rest position of the particle. r, κ, x_0 are the parameters of the trochoid. Knowing that the wave height is given by $H = 2r$, we can assume the significant wave height $H_{1/3}$ to be related to the wind speed V by

$$H_{1/3} = 7.065 * 10^{-3} V^{2.5} \tag{2.2}$$

Furthermore, we can express those equations as parametric equations of t if we assume that, for example, $x_0 = \alpha V t$ (with α a parameter) and that z_0 is constant. We then have the following set of parametric equations of the wind speed V and the time t, that already can describe ocean-shape-like surface:

$$\begin{cases} x(V,t) = \alpha V t + rsin(\kappa \alpha V t - \omega t) \\ z(V,t) = z_0 - rcos(\kappa \alpha V t - \omega t) \\ r(V) = \dfrac{3}{2} * 7.065 * 10^{-3} V^{2.5} \end{cases} \tag{2.3}$$

Those equations has the advantage of giving the possibility to easily compute the trajectory of one particle over the free surface along with its velocity.

This approach is deterministic and works for two dimensions but in reality, ocean waves are random in terms of both space and time. What follows is a stochastic approach for the modelization of ocean waves and is more complex to implement compared to the previous one. Following the Simulation of Ship Motion in Seaway report by Tristan Pérez and Mogens Blanke, we assume that :

- The observed sea surface is a realization of a stationary and homogeneous, zero mean Gaussian stochastic process.
- The spectral density function is known.

The sea elevation is given by the sum of individual sinusoidal contribution, and from an inertial frame, we can write that at (x, y) the sea elevation $\zeta(x, y, t)$ is given by:

$$\zeta(x,y,t) = \sum_{i=0}^{N} \zeta_i(x,y,t) = \sum_{i=0}^{N} \bar{\zeta}_i \cos(k_i x \cos(\chi) + k_i y \sin(\chi) + \omega_i t + \theta_i) \quad (2.4)$$

where $\zeta_i(x, y, t)$ is the contribution of the harmonic traveling wave components i progressing at an angle χ with respect to the inertial frame and with a random phase θ_i , k_i is the wave number, and ω_i the wave frequency seen from a fixed position.

For simplicity, we choose $\chi = 0$, (2.4) becomes

$$\zeta(x,y,t) = \sum_{i=0}^{N} \zeta_i(t) = \sum_{i=0}^{N} \bar{\zeta}_i \cos(\omega_i t + \theta_i) \quad (2.5)$$

Moreover, knowing the power spectral density $S(\omega)$, the amplitude of the wave components can be approximated [3] by

$$\bar{\zeta}_i = \sqrt{2 \int_{\omega_i - \frac{\Delta\omega}{2}}^{\omega_i + \frac{\Delta\omega}{2}} S(\omega)\, \mathrm{d}\omega} \quad (2.6)$$

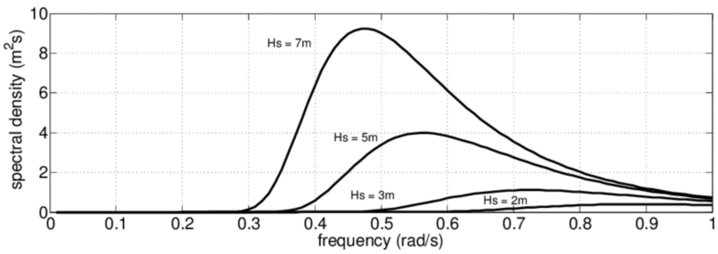
where $\Delta\omega$ is a band centered around ω_i.

For the power spectral density, we use the Modified Pierson-Moskowits spectrum given experimentally in terms of the significant wave height $h_{\frac{1}{3}}$ and the dominant wave period T

$$S(\omega) = S_{MPM}(\omega) = \frac{4\pi^3 h_{\frac{1}{3}}}{\omega^5 T^4} \exp(\frac{-16\pi^3}{\omega^4 T^4}) \quad (2.7)$$

where $h_{\frac{1}{3}}$ is the significant wave height, defined as the average height (trough to crest) of the one-third highest waves valid for the indicated period, and T is the wave period associated with highest energetic waves at a specific point or area in the total wave spectrum.

Figure 2.5: The MPM spectrum for different values of significant height



2.2.2 Ship Motion Model

To simulate the motion of a ship I thought about using a Response Amplitude Operator that I would apply on the previous signal generated with the MPM density spectrum but I could not find the literature corresponding to the establishment of such models with a closed formula. So I used two different techniques from [3] which were partly empirical. First, in order to create a realistic ship motion we proceed as we did with the sea elevation. Each components x_i of the boat's pose is defined as a sum of sine components

$$x_i(t) = \sum_{j=0}^{N} x_{ij}(t) = \sum_{j=0}^{N} \bar{x_{ij}} \cos(\omega_j t + \theta_j) \tag{2.8}$$

Each of the 6 components is then computed according to the geometry of the boat. We use a different filter each time which we apply on the spectral density function of the sea elevation. This filter are empirical approximations of what container ship motion is and with a fixed angle.

The other possibility which I found reasonable for the current application is the use of shaping filter of the following form:

$$H_{x_i}(s) = \frac{Ks}{s^2 + 2\xi\omega_n + \omega_n^2} \tag{2.9}$$

where K, ξ are empirically tuned in order to produce a realistic motion for the ship.

2.3 Stewart Gough Platform

2.3.1 Mechanical analysis

Due to the parallel structure of the platform, the payload is distributed to the six actuators, which allows larger payloads and better stiffness than comparable chain manipulators. However, the parallel structure makes it more difficult to control. Indeed, its inverse kinematics is easier to solve than in chain manipulators but the direct kinematics implies non linear equations that need to be solved.

In the present section we first address the inverse kinematics of the SGP, which is quiet straightforward, before presenting the direct kinematics problem. We will see that its not necessary in our case to solve it as we can get around using the controller.

2.3.2 Inverse Dynamics

For the SGP, the inverse kinematics consists of determining the length of the six legs in order to get a desired position and orientation for the upper platform according to a fixed reference frame. This can be done with geometrical considerations only. The inverse dynamics is important for this application because we want to place the upper platform into a desired position and orientation which we calculated before, using the last section.

Lets O_0 be the center of the fixed frame $\mathcal{F}$, O_1 the one of the moving frame $\mathcal{M}$. For each leg i we denote by l_i its length, more precisely, lets A_i be the attaching point of the leg i on the fixed platform and B_i the attaching point on the moving one. We have, using Chasles' relation that

$$\mathbf{l_i} = \mathbf{A_iB_i} = \mathbf{O_0O_1}_{\mathcal{F}} + R(\theta, \phi, \psi) * \mathbf{O_1B_i}_{\mathcal{M}} - \mathbf{O_0A_i}_{\mathcal{F}} \tag{2.10}$$

where $\mathbf{O_1B_i}_{\mathcal{M}}$ is expressed in the mobile frame, $\mathbf{O_0A_i}_{\mathcal{F}}$ in the fixed frame and $R(\theta, \phi, \psi)$ is the moving platform 's rotation matrix .

Suppose that we know the position and orientation of the platform $q = (x(t), y(t), z(t), \theta(t), \psi(t), \phi(t))$, then we know all the legs' length using (2.5). Indeed we have

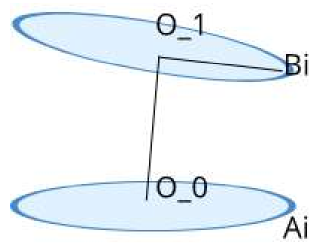
$$\mathbf{O_0O_1}_{\mathcal{F}}(t) = x(t)\mathbf{i_0} + y(t)\mathbf{j_0} + z(t)\mathbf{k_0} \tag{2.11}$$

$$\mathbf{O_1B_i}_{\mathcal{F}}(t) = R(\theta(t), \phi(t), \psi(t)) * \mathbf{O_1B_i}_{\mathcal{M}} \tag{2.12}$$

$$\mathbf{O_1B_i}_{\mathcal{M}}(t) = m_x^i \mathbf{i_1}(t) + m_y^i \mathbf{j_1}(t) \tag{2.13}$$

$$\mathbf{O_0A_i}_{\mathcal{F}} = f_x^i \mathbf{i_0} + f_y^i \mathbf{j_0} \tag{2.14}$$

Figure 2.6: Schema of the points on the SGP



where m_x^i , m_y^i and f_x^i, f_y^i are geometrical constants of the SGP. In our case, we don't have access to the vectors $\mathbf{A_iB_i}$ but to their norms $\|\mathbf{A_iB_i}\|$.

2.3.3 Direct Dynamics

Knowing the legs' length we want to know the corresponding orientation and position of the moving platform. Geometrically, it is equivalent to the problem of placing a rigid body such that six of its given points lie on six given spheres [6], which is a 40th degree polynomial with as many as 24 real solutions and is particularly challenging to solve.

To solve this, many iterative methods are used, but are quiet difficult to implement for embedded systems as the root-finding iterative process is time consuming.

In our current application, we do not need to solve the direct dynamics problem but we could estimate the pose of the moving platform using the six encoders as we will see in the command section of this chapter.

$$\begin{cases} \|l_1\|^2 = f_1(x_1, ..., x_6) \\ ... \\ \|l_6\|^2 = f_6(x_1, ..., x_6) \end{cases} \tag{2.15}$$

where the f_i are polynomials of $\mathbb{R}[X_1, ..., X_6]$. More precisely, lets $R(\theta(t), \phi(t), \psi(t)) = (r_{i,j})$, and $r_{\mathcal{M}}, r_{\mathcal{F}}$ are the radius of the moving and fixed platform.

$$
\begin{aligned}
f_i(x,y,z,\theta,\phi,\psi) = \quad & x^2+y^2+z^2+r_{\mathcal{M}}^2+r_{\mathcal{F}}^2 \\
& +2(r_{11}m_x^i+r_{12}m_y^i)(x-f_x^i)+2(r_{21}m_x^i+r_{22}m_y^i)(x-f_y^i) \\
& +2(r_{31}m_x^i+r_{32}m_y^i)z-2(xf_x^i+yf_y^i)
\end{aligned}
\tag{2.16}
$$

I also thought about applying an interval analysis method to solve the direct kinematics problem as in [13] but it also appeared to be not suitable for a real time application.

2.4 Command of the SGP

2.4.1 General Remarks

Due to its wide range of applications, the SGP command problem has a significant amount of publications detailing various strategies (e.g. Kalman filters[9], non-linear observers [11], etc.).

The main particularity that will shape the command of the platform here, are the sensors. The only sensors are the linear actuators' encoders which deliver a analogous signal (a voltage) informing us about the actual length of each legs. Therefore, we do not have measures of the platform's orientation. We also do not have the orientation of each leg, only its length. Coupled with the direct dynamics difficulty, we have to decide which approach is the most convenient regarding the expected behaviors of the SGP.

I tried to find a state-space representation in order to apply a feedback linearization method. I did find in [11] that the dynamics of the platform could be expressed by :

$$
M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=J^T(q)u \tag{2.17}
$$

where $M(q), C(q,\dot{q}), G(q), J^T(q)$ are the inertia matrix, the Coriolis and centrifugal matrix, the gravitational force and the Jacobian matrix of the SGP. With this, a state-space representation of the form :

$$
\begin{cases} \dot{x} = f(x)+g(x)u \\ y = h(x) \end{cases} \tag{2.18}
$$

But as it is specified in [12], the feedback linearization requires that the state to be completely accessible which was not the case here. I then tried and failed to implement a non-linear observer that would have made an estimation of the state.

2.4.2 Chosen model and Justification

The absence of estimation via sensors of the orientation of the moving platform and the practical difficulty of the direct dynamics resolution via numerical iteration naturally guided me to discriminate between different types of control.

A simple proportional-integral-derivative (PID) controller was used in the first place to control each leg. The velocity of the legs being computed from the data sheets. Indeed, I use the proportional relation linking the speed of the actuators with the current in the motor. We do not have a direct control over the actual platform position and orientation. To obtain it, I thought about using the non-linear observer of [12] and implement it under LabView but I hadn't had enough time to do so.

Figure 2.7: A simple PID control implementation

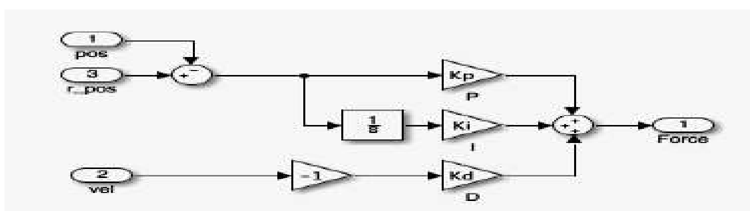
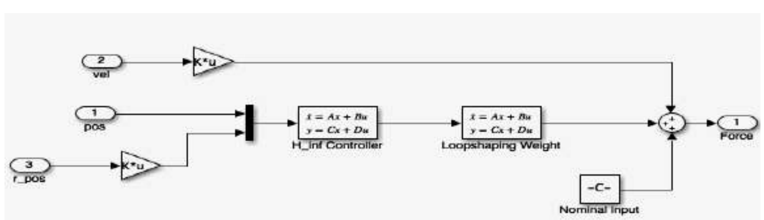


Figure 2.8: A H-infinity optimal control on Matlab



2.5 Simulation and experiments

Figure 2.9: the Stewart Platform of the laboratory

2.5.1 Simulation with Matlab Simulink

For the simulation I used the already made SGP model developed using SimMechanics that I found in the Mathwork's technical articles website. The state-space linear system obtained by linearizing around the equilibrium point of the platform is then used to implement a H-infinity optimal controller from the Control System Toolbox of Matlab.

2.5.2 Architecture of the experiment

In order to make the platform move I needed to acquire and generate signals from the actuators. This was done using a data acquisition system developed by National Instruments: the NI PX1-1045. This machine integrates different modules for the acquisition of analogous and digital signals. First, following

Figure 2.10: the NI PX1-1045 used to control the SGP

the previous experiment made by Ivanovich Selcado I thought about using the PXI 6143 to acquire the analogous voltage coming from the encoders as it was the only module available for the acquisition of analogous signals but I had to renounced because the cable linking the module to the NI-SCB100 (an I/O connector block) was not at my disposal in the laboratory. So the remaining possibility was to use the PXI-4472B which is a sound and vibration module so not quiet fit for the current application.

To generate the desired command signal for the motors, I used a motor driver called Sabertooth 2x12 because the PXI could not deliver a sufficiently high current for the actuators.

2.5.3 Implementation under LabView

LabView was installed on the PXI1-1045 as long with Matlab. The LabView environment was used to implement the PID controller and a script was used to generate the desired trajectory beforehand.

2.5.4 Set-up and Tests

It appears that I was too ambitious and that it was not as easy as I thought to assemble all the part needed for the tests. The set-up is represented in the annexes for two motors connected to one motor driver (there were 6 motors and 3 motor drivers) but 3 months were not enough to understand fully how the platform work, implement a realistic model of ocean waves, implement a control strategy, gather the parts for the SGP's control and activate the platform.

Chapter 3

Conclusion

The internship brought me to a country which I only knew for its wonderful music before, and was an enriching experience for me. Apart from my job at the university, I discovered people and places that made me reconsider some of my beliefs as I discovered the carioca's way of living. I also learn some rudiments of Portuguese and I am eager to continue learning, speaking and reading more Portuguese.

Professionally, I think that working alone the whole internship in order to see move the platform was quite challenging. I had real pleasure understanding how the SGP worked and how it could be used in different ways. I also learned how to use the LabView environment, how to control a linear actuator using a motor driver, how to implement different control techniques using Matlab, and various notions about wave modeling. All in all, despite the technical and material difficulties encountered, I was pleased to realize that I enjoyed the working environment of the laboratory.

In this work, the Stewart-Gough platform is used as a wave generator where each leg is controlled with PID and H-infinity optimal control using the inverse dynamics equations. The ship motion is obtained with a linear spectrum based modelization.

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Annexes

Figure 3.1: Specifications of the servo motors

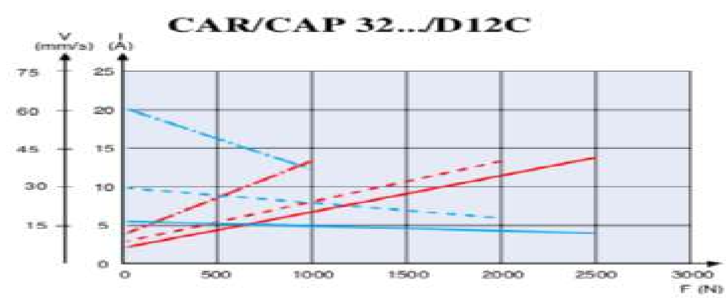

Figure 3.2: Specifications of the motor driver

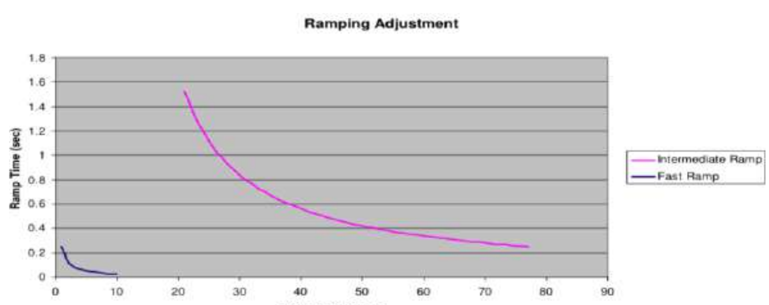

Figure 3.3: Connections for two motors with one motor driver