Ciência em Foco

VOLUME V

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APRESENTAÇÃO

A atividade científica tornou-se indispensável para a sociedade moderna. Os avanços nas mais diversas áreas das ciências têm vislumbrado a muitos, pois muitas das idealizações dignas da ficção científica hoje são realidades em nosso cotidiano. Todo o conhecimento produzido pela ciência e as técnicas dela derivadas têm contribuído para a evolução da sociedade em vários aspectos. Mesmo diante de todos esses evidentes benefícios para a humanidade, a crise sanitária que enfrentamos, que é decorrente da pandemia da COVID-19, colocou em xeque a credibilidade que a ciência, bem como os cientistas, possui perante alguns grupos sociais.

Nos últimos anos temos presenciado, com muito fervor, vários movimentos anti-vacinas e outros que advogam a utilização de tratamentos medicamentosos sem comprovada eficácia científica. Resultados de vários estudos têm sido deturpados a fim de embasarem certas narrativas, evidenciando uma ironia, pois tais indivíduos se utilizam de uma "ciência" forjada sem o método científico, com o propósito de apoiam suas crenças e questionam os resultados obtidos utilizando métodos científicos comprovados.

Pelas circunstâncias apresentadas, entendemos que a divulgação científica nunca foi tão necessária em nossa sociedade como é nos dias atuais. A Pantanal Editora tem a missão de apoiar esta divulgação, proporcionando aos cientistas, pesquisadores e investigadores um canal para promoção do conhecimento científico por eles produzidos. Já estamos no Volume V da Coletânea de e-books denominada de "Ciência em Foco". Essas coletâneas tem como objetivo a divulgação de pesquisas em quaisquer áreas do conhecimento.

Na presente coletânea vários tópicos são abordados nas mais diversas vertentes, desde pesquisas na área da educação, passando pela psicologia, literatura, farmacêutica, biologia e ciências agrárias, até aplicações avançadas nas áreas de engenharias. Esperamos poder contribuir com o arcabouço científico promovendo uma ciência de qualidade, impactante e acessível a todos.

Os organizadores

Sumário

Capítulo XVI

Model reduction of a 3RRR flexible parallel manipulator with experimental validation

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André Vecchione Segura[1*]

INTRODUCTION

Robotic manipulators are mechanical systems that allow the movement of a body in relation to a base. These systems are composed of kinematic chains, formed by bodies connected to each other by passive or active joints of normally one degree of freedom, that connect an end effector to the base. The end effector is a peripheral device attached to allow the robot to interact with the environment, such as grippers or welding torches. A loop is formed when the links of these chains connect in the shape of a polygon (Marghitu, 2005). Kinematic chains whose links and joints belong to one or more loops are called closed kinematic chains. Cinematic chains that do not have loops are called open kinematic chains. Manipulators with open kinematic chains are called serial manipulators, and manipulators with closed kinematic chains are called parallel manipulators.

Parallel manipulators (PM) have several potential advantages over serial manipulators, such as greater precision (Wu, 2015), higher stiffness (Luces et al., 2015) and greater dynamic performance (Wu, 2011). These advantages are partially attributed to the increased number of kinematic chains in the PM, allowing the distribution of efforts between the kinematic chains.

A possible strategy to increase dynamic performance and efficiency of the PM is the reduction of the mass of the links (Silva et al., 2010). These PMs with reduced mass are referred to as flexible parallel manipulators (FPM), and are capable of achieving higher speeds and a better ratio between operated load and link mass. However, the inertial and acting forces cause considerable deformations of the components and generate unwanted vibrations, impacting the accuracy and performance of the manipulator, making its implementation difficult.

Dynamic models of FPMs allow the examination of these dynamic characteristics and can be used to simulate changes in the FPM design and controller. For the simulation of the FPM a validated complete model is required, wich is normally incompatible with controller design due to its size. There are several approximations regarding the elaboration and reduction of these models, differing mainly in the formulation of the system flexibility and consideration of large movements and deformations.

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This work aims to build a multibody model based on finite elements of a 3RRR PM with the software COMSOL Multiphysics. The PM to be modeled can be seen in Figure 1 and is constructed at the Dynamics Laboratory of the São Carlos School of Engineering – University of São Paulo (EESC-USP). It has architecture 3RRR, consisting of 3 kinematic chains, consisting of an active revolution joint (R) and two passive revolution joints (RR). This model must cover the variable dynamics of the system. This variation can come from changes in temperature, manipulated load, and configuration of the PM. This model is validated by a modal analysis experiment. The link thickness is then reduced to simulate a FPM. The resulting flexible multibody model is then reduced for model-based control design.

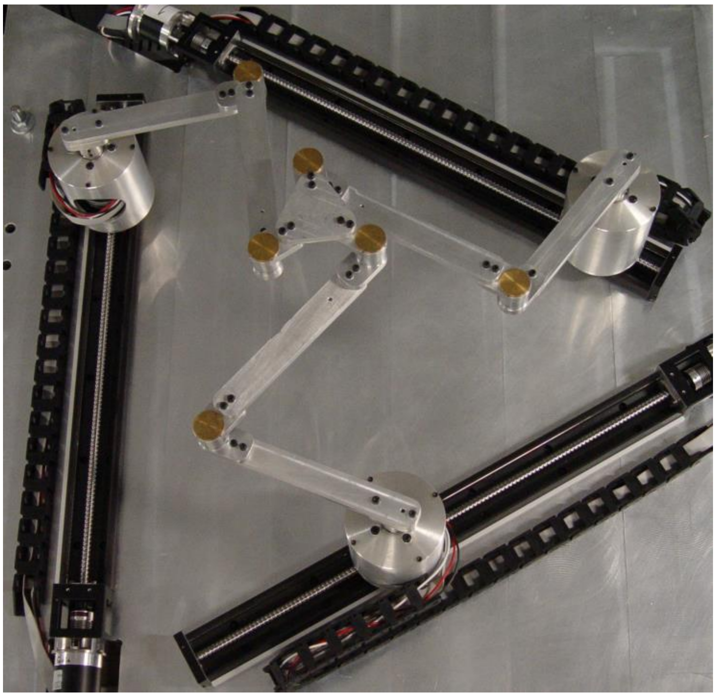

Figure 1. 3RRR parallel manipulator built at EESC-USP. Source: the author.

MODELLING OF THE PARALLEL MANIPULATOR

Considering the complexity of the system to be validated, it was decided to carry out the validation of subsystems, allowing the identification of isolated components. Two subsystems were defined: one composed exclusively of a link of the kinematic chain, and another composed of a kinematic chain with two links connected by a passive revolution joint. Building these models in COMSOL Multiphysics consists of the following steps: geometry elaboration, material selection, physical definitions, mesh construction, study setup, analysis and post processing of the results. The link subsystem is modeled as free-free and cantilevered, while the kinematic chain subsystem is fixed at both extremities.

The Multibody Dynamics Module was used to define the physics of the model, which consists of assigning equations for domains, surfaces, edges and points. These equations can be customized, developed by the user, or through options offered by the software. Among these options are definitions of joints, attachments, movement restrictions and application of forces or moments.

Attachments are groups of surfaces, edges, or points on a rigid or flexible component, used to connect it to a flexible component. To define a joint, two attachments are used, one of origin and one of destination. Passive revolution joints are defined as hinge joints, that do not allow elastic deformation and have only one degree of freedom, in which the attachment of destination rotates freely in relation to the origin. Active revolution joints are defined as rigid connectors, which make possible to restrict or prescribe displacements and rotations for each coordinate.

Table 1. Values of the first two frequencies of the link for different meshes. Source: the author.

Mesh		Free-free link		Cantilever link	
Size	Elements	1st Freq. (Hz)	2nd Freq. (Hz)	1st Freq. (Hz)	2nd Freq. (Hz)
Normal	2091	2033,3	2165,9	294,98	354,19
Fine	6301	1732	1795,1	266,14	309,75
Finer	26477	1280,5	1295,6	253,14	270,94
Extra fine	59658	1122,1	1146,6	22,41	254,04
Extremely fine	148327	1018,9	1071,9	212,67	246,61
Custom	22560	988,97	995,46	203,04	235,51

Table 1 shows the first two eigenfrequencies of the free-free link and of the kinematic chain. Normal to extremely fine meshes refer to the automatic options offered by the software, the custom mesh is controlled by the user. In the custom mesh, the main modification was the creation of a swept mesh: the mesh of one face is projected through the component, creating identical layers. Face elements are triangular, and projected elements are prismatic.

The mesh of the kinematic chain presents greater variation in the result for alterations in the mesh in the links than in the joints, specifically the distribution of the elements. The distribution is done by defining the number of elements connected to the longest edge of the link. A partial adaptive mesh study of the software also indicated this region of the link as the most relevant for the accuracy of the result. Table 2 shows the convergence of the result when changing the distribution of elements in the link of the kinematic chain. The joint mesh has tetrahedral and prismatic elements.

Table 2. Values of the first natural frequency of the kinematic chain for different mesh settings. Source: the author.

Mesh	Elements distributed	Total elements	Frequency (Hz)
Finer	Standard	29847	104,46
	20	29827	94,551
	40	331437	83,375
	60	33777	79,552
	80	36277	78,623
	100	40337	77,831
Extremely fine	Standard	124508	101,94
	20	124258	101,31
	40	125978	82,931
	60	1280098	78,984
	80	130968	77,778
	100	134588	77,235

The manipulator mesh was constructed based on the chain mesh. Table 3 shows the convergence of the result for different meshes for the same position of the manipulator. For each manipulator position changes can be made to the mesh that best approximate the result. This practice however becomes unfeasible due to the high number of positions. Therefore, the mesh with the smallest error was used for all the positions, within the limit of the size supported by the hardware. The end effector mesh was made by the same method used for the links: a triangular mesh of one of the faces projected to the opposite face, forming prismatic elements.

Table 3. Values of the first natural frequency of the manipulator for different meshes. Source: the author.

Mesh	Elements distributed	Total elements	Frequency (Hz)
Finer	Standard	130648	69,897
	20	131064	65,273
	40	138824	62,391
	60	147254	61,555
	80	156844	61,351
Extremely fine	Standard	108004	63,276
	20	07929	63,563
	40	115124	62,098
	60	122319	61,828
	80	130459	61,677

The distortion, recommended for most cases, was used as the metric for the quality of the mesh elements. Quality 1 elements are ideal, lower quality that 0.1 should be avoided for most studies. Figure 2a shows statistics for this mesh, with the minimum and average quality of the elements being the most important parameters for evaluation of the mesh. The histogram shows the distribution of the quality of the elements, going from 0 to 1 from left to right. Figure 2c presents the elements with quality less than 0.5. The elements of lower quality belong exclusively to the joints and engine flanges.

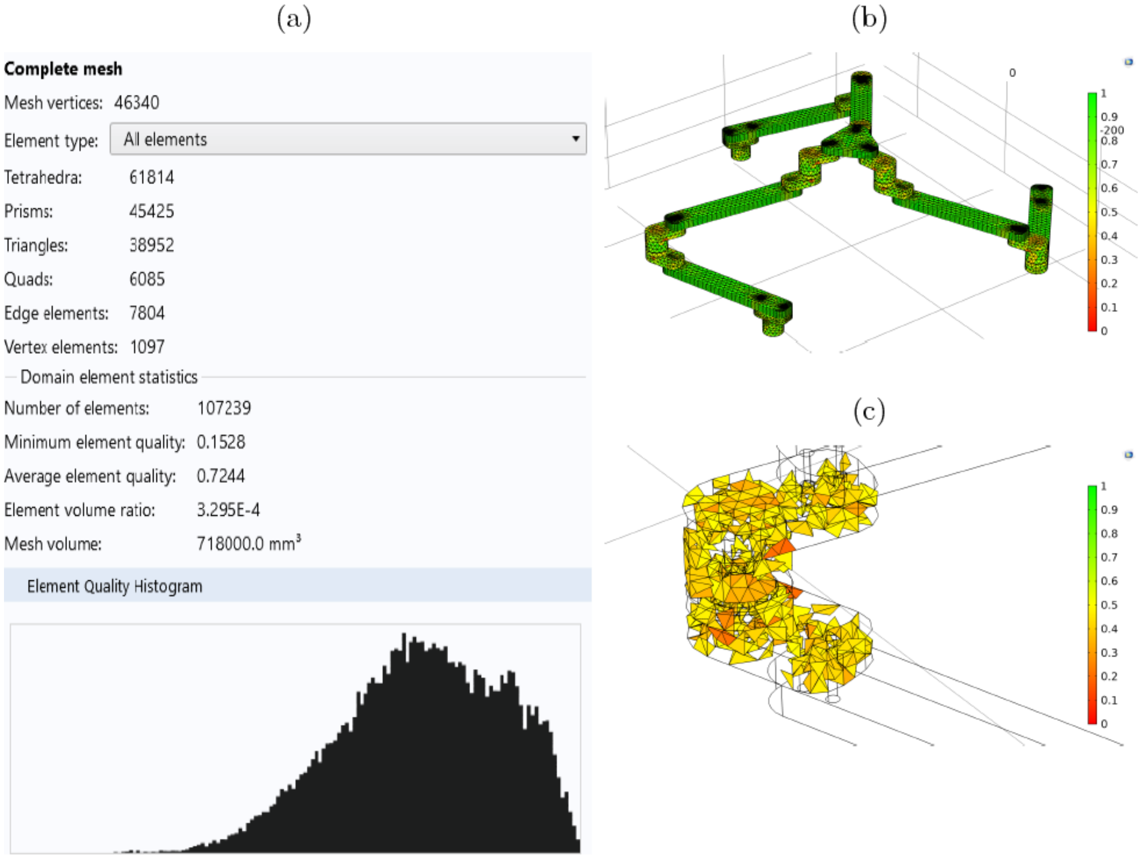

Figure 2. 3RRR manipulator mesh characteristics: (a) mesh statistics; (b) plot of element quality; and (c) plot of elements with lower quality. Source: the author.

EXPERIMENTAL VALIDATION

The validation was performed by comparing the first natural frequency determined by the software with the first frequency found through a modal analysis experiment. In carrying out the experiment were used PCB 352A24 uniaxial accelerometers, the Impact hammer PCB 208C02 force sensor and the Data Physics Quattro acquisition system. Data from the average of three impacts are used to formulate the FRF, and the first frequency is determined by interpreting the position of the peaks. The positions of the accelerometers are marked in the images. Validation of subsystems is presented first, followed by handler validation. The manipulator experimented had 30mm links, while the subsystems links had a thickness of 10mm. The acquisition method is the same for all experiments. All the setups of the experiment can be seen in Figure 3.

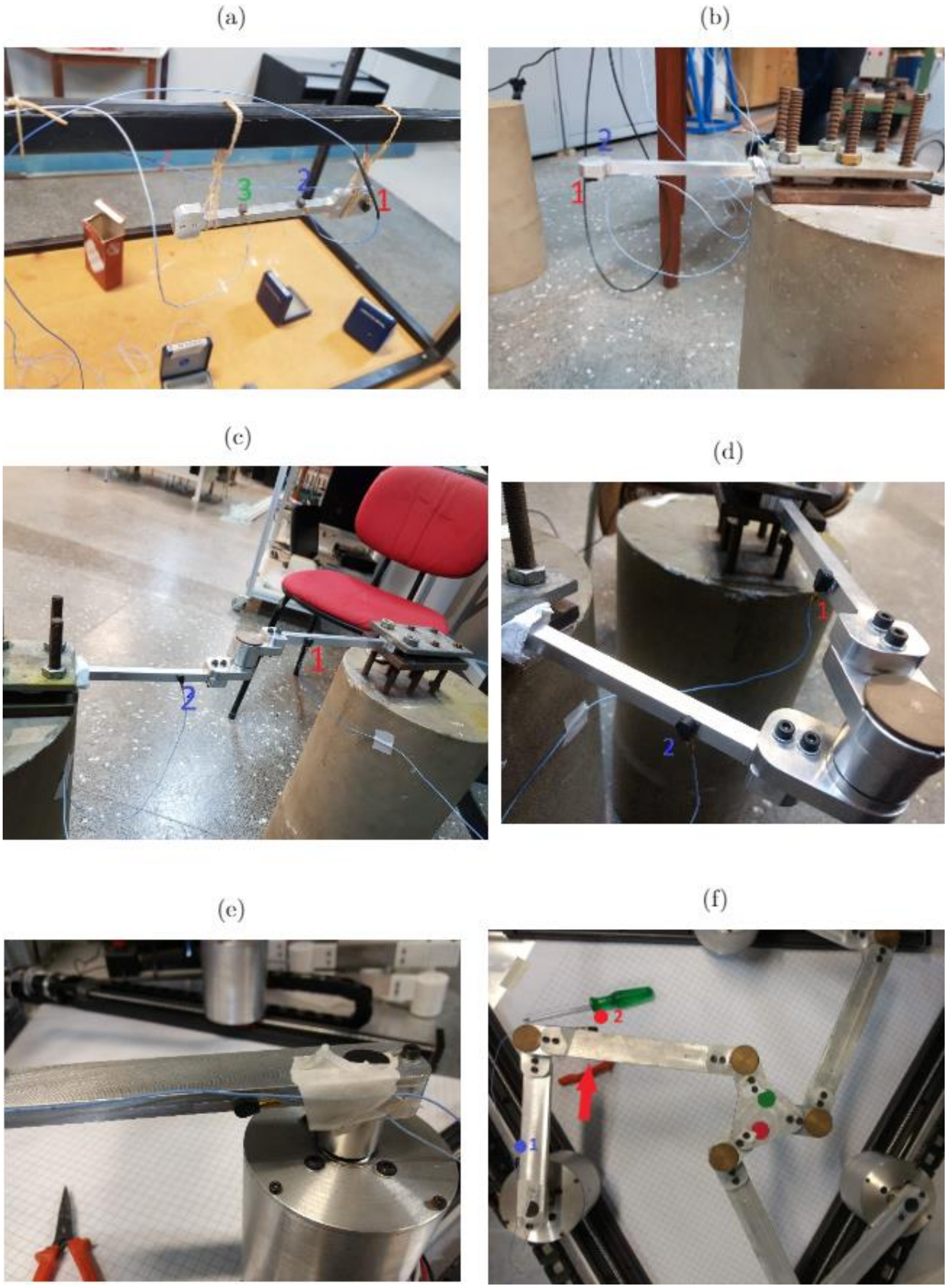

Figure 3. Setup of the experiments: (a) free-free link; (b) cantilevered link; (c) 180º kinematic chain; (d) 60º kinematic chain; (e) fixation of the accelerometers on the PM; and (f) MP with impact direction highlighted. Source: the author.

Experiments were carried out with the link under two conditions: free-free, suspended by elastic bands, Figure 4a, and with one of its ends embedded in a concrete cylinder. The free-free experiment is easier to replicate and allows to study the required resolution of the mesh. The second allows you to determine the best definition in COMSOL for the fixation used in this and the next experiments. The impact was delivered at the free end of the link. Interpreting the amplitude of the Frequency Response Function (FRF) it is possible to identify well-defined peaks for both experiments. Peaks at different frequencies between accelerometers are noticeable, especially for the fixed link. This difference can be attributed to the form of the first mode, with amplitude mostly in one direction, which is not captured by both accelerometers. The experimental results for the first eigenfrequency are 985 and 221 Hz for the free-free and cantilevered link, respectively. The theoretical results are 988,97 and 203,04 Hz for the respectives links. The percentage error is 0,40% for the free-free link and 8,12% for the cantilevered link. The higher error for the cantilevered experiment can be attributed to the difficulty in modelling the connection with the concrete cylinder, which is not completely rigid.

For the kinematic chain experiment, both ends were fixed in concrete cylinders, and the angle in the joint was changed. Three angles were considered: 180, 90 and 60 degrees. The experiment was repeated with impact on different points, impacting the joint resulted in clearer data. The experimental results are 79, 88, and 81 Hz for the setup at 60, 90, and 180 degrees, respectively. The theoretical results are 80,86 Hz, 89,83 Hz, and 80,97 Hz in the same order. The maximum error was 1.86 Hz and the average error was 1.24 Hz.

Table 4. Values in Hz of the first experimental eigenfrequency. Source: the author.

y (mm) / x (mm)	-100	-50	0	50	100
100	50	48	47	49	50
50	54	50	60	-	57
0	29	54	62	-	35
-50	-	-	-	36	35
-100	73	63	-	-	35

The manipulator experiment was repeated for twenty-five different positions, in order to account for the variation of the dynamics of the system, depending on its configuration. To position the manipulator in specific settings, a circumference concentric to the coordinate system, and containing the center of rotation of the motors, was draw on the plane of the base, along these coordinates circles whose centers are 50mm apart were drawn. The manipulator is positioned by centering the end effector with these circles. Each position of the manipulator will then be referred to by its position in this plane. The position control was done by the manipulator software, and the motors remained locked during impact, delivered on the same axis as the accelerometer of the second link. To avoid singularity, the end effector was rotated 0.2 rad in the experiments at the coordinates (x, 0). Table 4 shows the experimental results and Table 5 shows the theoretical results.

Table 5. Values in Hz of the first theoretical eigenfrequency. Source: the author.

x (mm) \ y (mm)	-100	-50	0	50	100
100	50,69	43,29	45,90	53,13	52,57
50	54,63	44,29	54,45	-	50,30
0	27,14	60,96	61,37	-	32,63
-50	-	-	-	34,35	35,72
-100	74,56	59,39	-	-	35,81

Some positions presented results difficult to interpret, making it impossible identify with certainty the first frequency, both by observing the FRF and by using MATLAB functions. These settings are marked with a (-) in the tables. The low quality of data collected is attributed to the distribution of links in space, which maked it difficult to apply single impacts with adequate force, and had greater system damping. Compared to the link and chain models, the error found is greater, as a result of the greater complexity of the system and the smaller mesh resolution. As the manipulator model is larger, keeping the element size used in the first models results in a very large amount of elements, impossible to resolve by the available hardware. The minimum error is 0,63 Hz or 1,01%, the maximum error is 6,96 Hz or 12,88%, the average error is 2,88 Hz or 5,84%, the median is 2,11 Hz or 5,43%. Considering the large number of configurations simulated by the model, moderate errors are expected. Closer positions, avoiding conditions that make it difficult to experiment and with less variation in dynamics, would probably provide more accurate results.

MODEL REDUCTION

Low order models, obtained by model reduction methods, are needed for controller design and for repetitive, cost-effective simulation of computational models. Several reduction techniques have been developed based on modal contribution, data approximation, etc. Component Mode Synthesis (CMS) (Seshu, 1997) is a substructure technique which aims to determine the behavior of the system through the combination of its components, basically, it consists in finding the equations of motion of each substructure, which when coupled describe the complete system in a reduced way. This method can be employed on systems whose dynamic performance is dependent on its configuration, since these substructures have a determined relative position. A disadvantage of this method is the need to maintain the elements that connect the components to one another, sometimes requiring a second reduction by another method.

Whereas large models cannot always be reduced enough by CMS, approximation based reduction methods can be a solution. In these methods, a subspace that best approximates the relationship between input and exit from the system. Singular Value Decomposition (SVD), Krylov subspace, and combinations of both are examples of techniques that use this method. When designing a model that better approach the input and output relationship of the system, it may not have terms related to mass, stiffness, or modal matrix. This lack of physical meaning makes it difficult to evaluation of manipulators, both serial and parallel, during the project. A review of these methods can be found in the work of Antoulas et al. (2001).

Techniques based on GMP, such as the one proposed by Brüls et al. (2007), can produce models with a great degree of reduction, maintaining their physical meaning. In GMP the system is described by the contribution of global modes, considering the system as a whole. These dominant modes depend on the system configuration, which can be parameterized. For the definition of the GMP consider the following equations of generalized movement of a flexible multibody system:

$$M(q)\ddot{q} + B^T\lambda = g(q, \dot{q}, t)$$

$$\Phi(q, t) = 0$$

M is the mass matrix, **g** is the internal and external inertial forces, **B** is the matrix of constrait gradients, and λ are the internal forces caused by constraints. Considering de augmented coordinate $\mathbf{v} = [\mathbf{q}]^T$, GMP is in summary the mapping between **v** and the modal coordinates $\boldsymbol{\eta}$.

The Reduced Order Model (ROM) built by COMSOL consists of a black box trained using data from a user-determined study, in a way to produce the same outputs as the full model. Three studies are used for the construction of this model: Time Domain, Eigenvalues, and Model Reduction. The first study, which can be in both the time and frequency domains, defines the model to be reduced, the second provides the training data, and the third builds the ROM, with user-defined inputs and outputs. The construction of these ROMs can be computationally expensive due to the production of training data. Each ROM is valid for a small variation of its parameters, so, in the case of the manipulator under study, it is necessary to build a ROM for each configuration relevant to the application, due to the variation of the dynamic of the system.

The ROM constructed has the manipulator at position (0,0). To validate the reduced model, a study was run with both the non-reduced and the reduced model. In this study, a constant force was applied in the end effector in the x and y direction, with the motor joints fixed, the displacement of the end effector over time, due to link flection, is the compared. For this study the link thickness of all links was set to 5 mm. The study lasts 0.2 seconds with a step of 0.1 milliseconds. The results can be observed in Figure 4 The small step was chosen to reduce the numerical damping coming from the approximation of the solution. The simulation time was 4 minutes 32 seconds for the non-reduced model and instant for the reduced model. The models have good agreement, with a small difference in amplitude, especially at the first peak and the first valley. The larger displacement in the y direction is attributed to the links configuration, that provided greater resistance to displacements in the x direction. The matrices, inputs and outputs, and other data from both the non-reduced model and the reduced model can be exported and accessed in MATLAB/Simulink for investigation, simulation, and model based control design, among other uses.

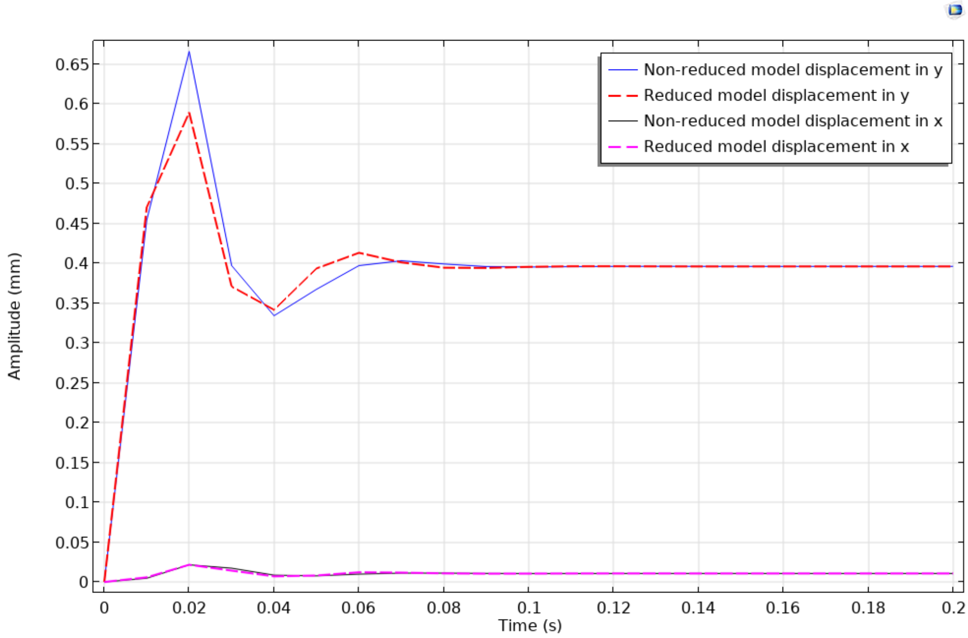

Figure 4. Displacement over time for the reduced and non-reduced model. Source: the author.

CONCLUSION

The reduction of the mass of the components of parallel manipulators can bring a number of benefits, such as increased dynamic performance and lower energy consumption, but at the cost of losing the system's stiffness. These manipulators with reduced rigidity they are called flexible manipulators, and are more susceptible to vibrations. Dynamic models allow to investigate this flexibility, being very useful to the study of the dynamic behavior of the system and for the design of controllers. A major challenge of this type of system is the variable, configuration dependent dynamics.

In this work, a flexible multibody model in finite elements of the 3RRR planar parallel manipulator was elaborated using COMSOL Multiphysics. For model validation, a modal analysis experiment was conducted on a prototype of the manipulator. To account for the variable dynamics of the system, the experiment was repeated for 25 configurations. Of these configurations, 7 showed results difficult to interpret, and were disregarded in the validation. The error between theoretical and experimental values was at most 6.96 Hz (12.88%) and on average 2.88 Hz (5.84%). The model construction was presented and mesh considerations were discussed. The model allows quick changes to its configuration and geometry, making it useful as reference for changes in the design of its components, especially the thickness of the links.

The reduced model found is valid for simulations close to the configuration of the complete training model, therefore, multiple models are needed, and their interpolation provides intermediate settings. The construction of multiple reduced models can be costly, due to obtaining training data.

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ÍNDICE REMISSIVO

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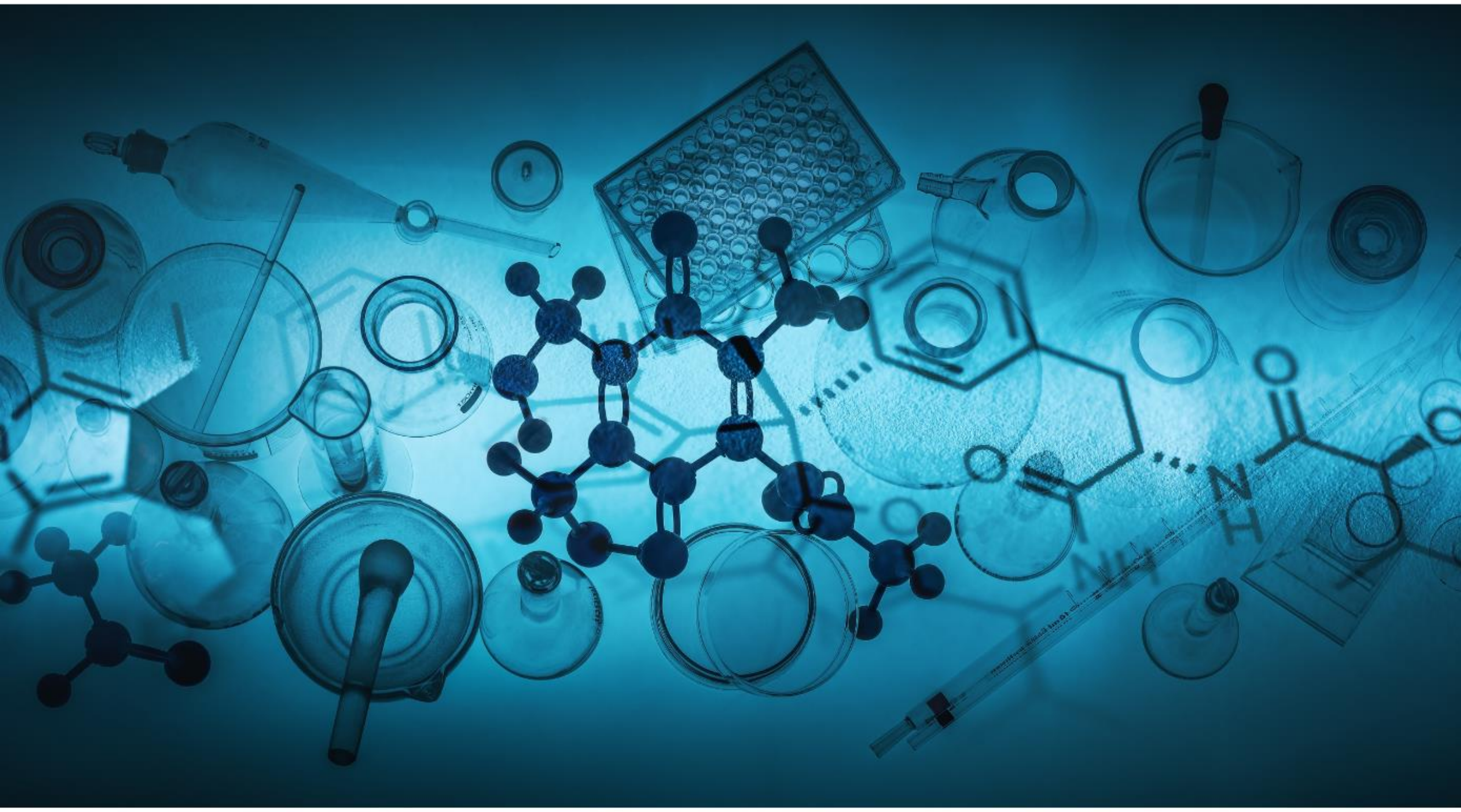

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