

## EQUILIBRIUM CONDITIONS OF A CLASS I TENSEGRITY STRUCTURE

Robert E. Skelton<sup>1</sup>, Darrell Williamson<sup>2</sup>, JeongHeon Han<sup>3</sup>

### ABSTRACT

Static models of tensegrity structures are reduced to linear algebra problems, after first characterizing the problem in a vector space where direction cosines are not needed. That is, we describe the components of all member vectors as opposed to the usual practice of characterizing the statics problem in terms of the magnitude of tension vectors. While our approach enlarges (by a factor of 3) the vector space required to describe the problem, the computational space is not increased. The advantage of enlarging the vector space makes the mathematical structure of the problem amenable to linear algebra treatment. Using the linear algebraic techniques, many variables are eliminated from the final existence equations. This paper characterizes the existence conditions for all tensegrity equilibria.

**Key Words:** tensegrity, structure, statics, equilibrium conditions, linear algebra.

### INTRODUCTION

The Tensegrity structures introduced by Kenneth Snelson pose a wonderful blend of geometry and mechanics. In addition, they have engineering appeal in problems requiring large changes in structural shape. We define "class I" tensegrity as a stable connection of bars and strings with only one bar connected to any given node. Nodes connecting more than one bar or other constraints form "class II" tensegrity. Thus, class I structures are unconstrained, whereas, class II may have boundary constraints or bar to bar connections. Most existing *smart structure* methods are limited to small displacements. Since class I tensegrity structures [8] have no bar-to-bar connections, the control of tendons allows very large shape changes. Therefore, an efficient set of analytical tools could be the enabler to a hoist of new engineering concepts for deployable and shape controllable structures.

This paper characterizes the static equilibria of class I tensegrity structures. Furthermore, we use vectors to describe each element( bars and tendons), eliminating the need to use direction cosines and the subsequent transcendental functions that follow their use.

It is well known in a variety of mathematical problems that enlarging the domain in which the problem is posed can often simplify the mathematical treatment. For example, nonlinear Riccati equations are known to be solvable by linear algebra in a space that is twice the size of the original problem statement. Many nonlinear problems admit solutions by linear techniques by enlarging the domain of the problem. The purpose of this paper is to show that by enlarging the vector space in

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Libration Point Orbits and Applications G. Gómez, Martin Wen-Yu Lo, Josep J. Masdemont, 2003 This work presents the state of the art in numerical and analytical techniques as well as future trends associated with mission design for libration point orbits. It contains papers explaining theoretical developments and their applications including the accurate description of some actual libration point missions of ESA and NASA. The existing software in the field and some applications beyond the neighbourhood of the Earth are also presented. Special emphasis is placed on the use of dynamical system methodology in the libration point orbits mission design      **Astrodynamics Network AstroNet-II** Gerard Gómez, Josep J. Masdemont, 2016-07-29 These are the proceedings of the AstroNet II International Final Conference. This conference was one of the last milestones of the Marie Curie Research Training Network on Astrodynamics AstroNet II that has been funded by the European Commission under the Seventh Framework Programme. The aim of the conference and thus this book is to communicate work on astrodynamics problems to an international and specialised audience. The results are presented by both members of the network and invited specialists. The topics include trajectory design and control, attitude control, structural flexibility of spacecraft and formation flying. The book addresses a readership across the traditional boundaries between mathematics, engineering and industry by offering an interdisciplinary and multisectorial overview of the field

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as the optimization of static systems special boundary conditions and dynamic equality constraints An analytical approach is focused on throughout as opposed to computational The result is a book that emphasizes simplicity and practicability which makes it accessible and engaging This holds true in later chapters that involve orbital mechanics two body maneuvers bounded inputs and flight in non spherical gravity fields The intended audience is primarily upper undergraduate students graduate students and researchers of aerospace mechanical and or electrical engineering It will be especially valuable to those with interests in spacecraft dynamics and control Readers should be familiar with basic dynamics and modern control theory Additionally a knowledge of linear algebra variational methods and ordinary differential equations is recommended

*Analytical Solutions for Extremal Space Trajectories* Dilmurat M. Azimov, 2017-08-23 *Analytical Solutions for Extremal Space Trajectories* presents an overall treatment of the general optimal control problem in particular the Mayer's variational problem with necessary and sufficient conditions of optimality It also provides a detailed derivation of the analytical solutions of these problems for thrust arcs for the Newtonian linear central and uniform gravitational fields These solutions are then used to analytically synthesize the extremal and optimal trajectories for the design of various orbital transfer and powered descent and landing maneuvers Many numerical examples utilizing the proposed analytical synthesis of the space trajectories and comparison analyses with numerically integrated solutions are provided This book will be helpful for engineers and researchers of industrial and government organizations and is also a great resource for university faculty and graduate and undergraduate students working specializing or majoring in the fields of aerospace engineering applied celestial mechanics and guidance navigation and control technologies applied mathematics and analytical dynamics and avionics software design and development Features an analyses of Pontryagin extremals and or Pontryagin minimum in the context of space trajectory design Presents the general methodology of an analytical synthesis of the extremal and optimal trajectories for the design of various orbital transfer and powered descent and landing maneuvers Assists in developing the optimal control theory for applications in aerospace technology and space mission design

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modelling and understanding of the thermosphere system and its interactions with the lower atmosphere the ionosphere magnetosphere system and the Sun

**The Journal of the Astronautical Sciences** ,2005

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**Fundamentals of Astrodynamics and Applications** D.A. Vallado,2001-06-30 Fundamentals of Astrodynamics and Applications is rapidly becoming the standard astrodynamics reference for those involved in the business of spaceflight What sets this book apart is that nearly all of the theoretical mathematics is followed by discussions of practical applications implemented in tested software routines For example the book includes a compendium of algorithms that allow students and professionals to determine orbits with high precision using a PC Without a doubt when an astrodynamics problem arises in the future it will become standard practice for engineers to keep this volume close at hand and look it up in Vallado While the first edition was an exceptionally useful and popular book throughout the community there are a number of reasons why the second edition will be even more so There are many reworked examples and derivations Newly introduced topics include ground illumination calculations Moon rise and set and a listing of relevant Internet sites There is an improved and expanded discussion of coordinate systems orbit determination and differential correction Perhaps most important is that all of the software routines described in the book are now available for free in FORTRAN PASCAL and C This makes the second edition an even more valuable text and superb reference

Assessment of Tensegrity Structures Paulina Obara,2025-06-19 This book enables a proper understanding of tensegrity structures It contains both theoretical background and examples First a geometrically non linear model and the methods used to evaluate the behavior of tensegrity structures are explained Next a broad spectrum of

different planar and spatial design solutions is considered Assessment of Tensegrity Structures is very logically organized in line with its down to earth subject beginning with the simplest two dimensional structure for which solutions can be presented in explicit form and ending with more complex tensegrity structures used in civil engineering such as domes towers and plates This book is designed for everyone who is interested in tensegrity systems from beginners to those who want to deepen their knowledge of them The Open Access version of this book available at <http://www.taylorfrancis.com> has been made available under a Creative Commons Attribution CC BY 4.0 license

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comment cuisiner un sanglier cuissons - Jan 29 2022

web jul 27 2021 vous pouvez faire cuire du sanglier sur le gril ainsi que des steaks ou des cuisses coupées en tranches faites mariner la viande dans un mélange d'huile d'olive d'ail haché de persil haché de sel et de poivre réservez au réfrigérateur au



moins 1 heure avant la cuisson filet mignon est placé à l'intérieur du porte côtes

*sanglier viande ferme prix cuisson journal des femmes cuisiner* - Feb 27 2022

web aug 31 2022 comment cuisiner et déguster le sanglier le sanglier est une viande ferme ce qui est dû à sa richesse en collagène et en élastine c'est pourquoi il est recommandé de la faire mariner dans un mélange de vin d'épices et d'aromates

*recette de bourguignon de sanglier facile marmite* - Feb 10 2023

web 27 commentaires 1 h 50 min facile bon marché mon carnet partager ingrédients 8 personnes 200 g de lardons 50 g de beurre 2 oignons ou même l'équivalent en oignons émincés surgelés 4 c à s de farine poivre sel 4 carottes 800 g de sanglier 75 cl de vin rouge 3 ail ou de l'ail semoule 1 bouquet garni 250 g de champignon de paris en boîte

**recette de sanglier 32 recettes sur ptitchef** - Jan 09 2023

web 32 recettes Évoluant en horde le sanglier est un porc sauvage au corps très musclé sa viande comportant peu de matières grasses est considérée comme maigre elle peut se préparer en sauce en terrine par mesure de sécurité sanitaire elle doit être bien cuite

*cuisson du sanglier notrefamille com* - Dec 08 2022

web jan 9 2014 le sanglier est un mammifère omnivore particulièrement apprécié pour sa saveur unique en cuisine il peut être préparé de plusieurs façons pour les amateurs de ce cochon sauvage voici quelques idées de cuisson pour le plus grand plaisir de vos papilles sommaire astuces pour réussir la cuisson du sanglier cuissot de sanglier rôti

recettes faciles de sanglier recettes de gibiers cuisine az - Jul 15 2023

web parce que nous aussi on l'adore on vous a trouvé les meilleures façons de cuisiner le sanglier et il y aura le choix un beau gigot de sanglier pour le déjeuner familial un savoureux rôti de sanglier pour régaler les amis une épaule de sanglier pour éblouir les connaisseurs ou un vrai cuissot pour les soirs d'hiver

**sanglier marmite** - Apr 12 2023

web 65 recettes filtrer daube de sanglier au cognac 4 6 5 96 avis cuissot de sanglier d'obélix au four 4 8 5 51 avis marinade pour biche chevreuil sanglier 4 9 5 39 avis cuissot de sanglier chevreuil ou biche 4 6 5 67 avis cuissot de sanglier de 7 heures 4 7 5 42 avis filet de sanglier rôti 4 9 5 29 avis

sanglier de 7 heures recette pour 8 personnes la petite - Dec 28 2021

web couvrez et enfournez pour 7 heures sortez la cocotte du four et sortez la viande de la cocotte réservez mettez la cocotte sur feu vif et faites réduire de moitié la sauce ajoutez la crème de marron et la crème fraîche et laissez épaissir quelques instants servez le sanglier à la cuillère et la sauce à part

recette sanglier cuisine az - Jun 02 2022

web sanglier ingrédients de la recette 1 cuissot de jeune sanglier de 3 kg environ 200 g de lard gras 4 gousses d'ail 6

échalotes baies de genièvre avant de commencer la cuisson pelez les oignons et les carottes puis émincez les etalez les couennnes dans une grande cocotte en fonte ajoutez les carottes et les oignons en les

recettes au sanglier mijoté au four en sauce journal des - Aug 16 2023

web mar 6 2022 réglez vous avec cette sélection pour cuisiner le sanglier autrement avec des préparations faciles ou gastronomiques les recettes au sanglier sont propices à de gargantuesques festins familiaux notamment durant la période de Noël

cuisiner le sanglier 50 recettes originales chassons com - Jun 14 2023

web sep 23 2019 la viande de sanglier est délicieuse goûteuse et peu onéreuse elle est facile à trouver en saison avec des qualités nutritionnelles exceptionnelles il y a mille façons de les accommoder pour une cuisine du quotidien autant que festive

**recettes de sanglier la sélection de 750g** - Mar 31 2022

web recettes de rôti de sanglier sanglier sanglier le sanglier est apprécié pour son goût prononcé à marier en terrine ragoût rôti ou civet a servir avec un bordeaux ou un bourgogne

**sauté de sanglier recette de sauté de sanglier marmiton** - Aug 04 2022

web pour la cuisson 2 c à s d huile d olive 1 c à s de farine sel poivre pour la marinade 5 cl de vinaigre balsamique 5 cl d huile d olive 2 carottes en rondelles 4 clous de girofle 10 grains de poivre 1 belle branche de thym 1 feuille de laurier 1 bouteille de vin rouge corsé 1

**comment cuisiner le sanglier marie claire** - Sep 05 2022

web conseils pour cuisiner comment cuisiner le sanglier par internaute cvf meilleure réponse par nos experts par maurice brulot la terrine de sanglier se fait sur plusieurs jours dans un