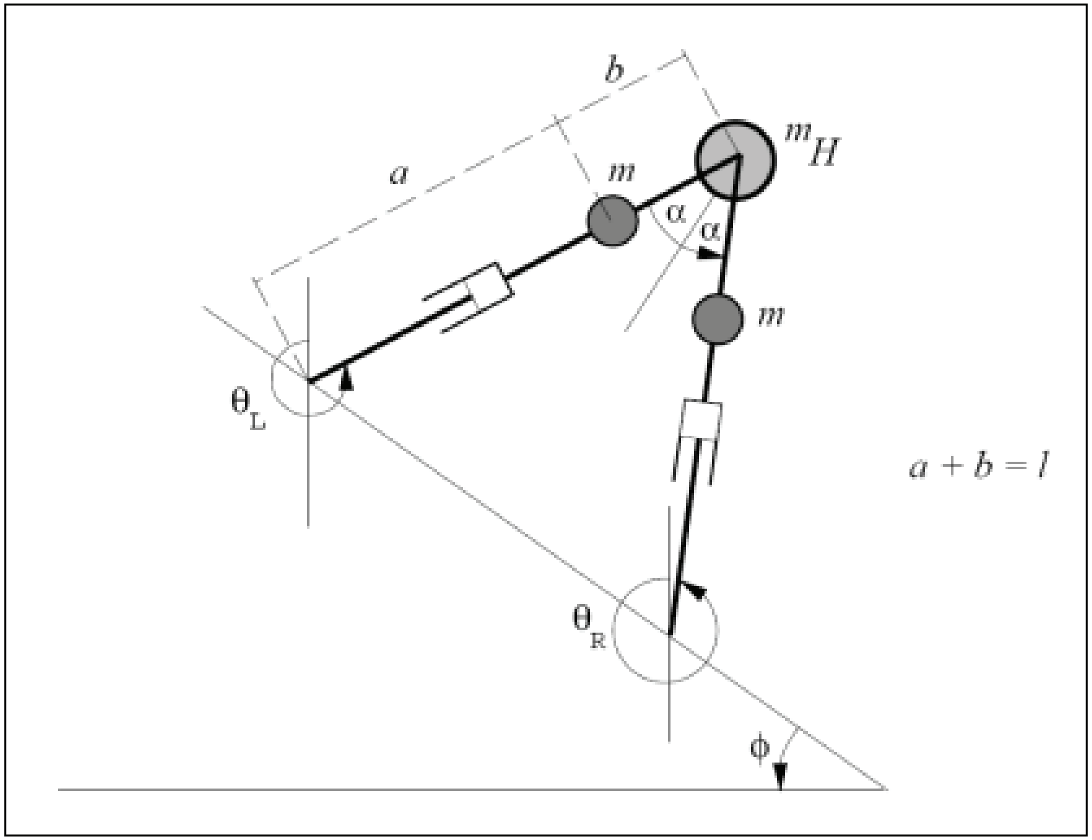
Bernard Espiau
and the Resurrection of Compass Gait Robots
(History of 4 years and 6 papers)



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June 8, 2012


Photo: Philippe Garnier (SHARP)

Historical Picture: INRIA Building Construction1995

Where have I been all these years?

Sept, 1993 – Jan, 1998: INRIA (INPG @ Felix Viallet -> Montbonnot)

Jan, 1998 – May, 1998: University of Illinois, Urbana-Champaign

June, 1998 – June, 1999: University of Pennsylvania, Philadelphia

July, 1999 – May, 2002: Autodesk, Discreet, San Francisco

June, 2002 – present: Honda Research Institute, Mountain View

Current status of “compass gait”:

- Bernard or I have not worked on “compass gait” after 1997.

- Prof. Ken Waldron at Stanford University asked me to make a presentation on compass gait in 2003.
  I used transparency slides prepared 5 years earlier

  I said,
  1. This is the last time I am using transparencies
  2. This is my last presentation on compass gait

- I was wrong on both points!!

- 2010: JAIST, Japan, Locomotion Summer School
- 2011: University of Umea, Sweden

How I was inducted into the study of compass gait

Going back… In 1993:

- Fresh outside my graduate school (Northwestern University, IL, USA)
    - Robot-assisted surgery
    - Robot impedance control

- Bernard Espiau, a researcher well known in visual servoing gave me a post-doctoral appointment at INRIA and said we will work on biped robots in Grenoble …

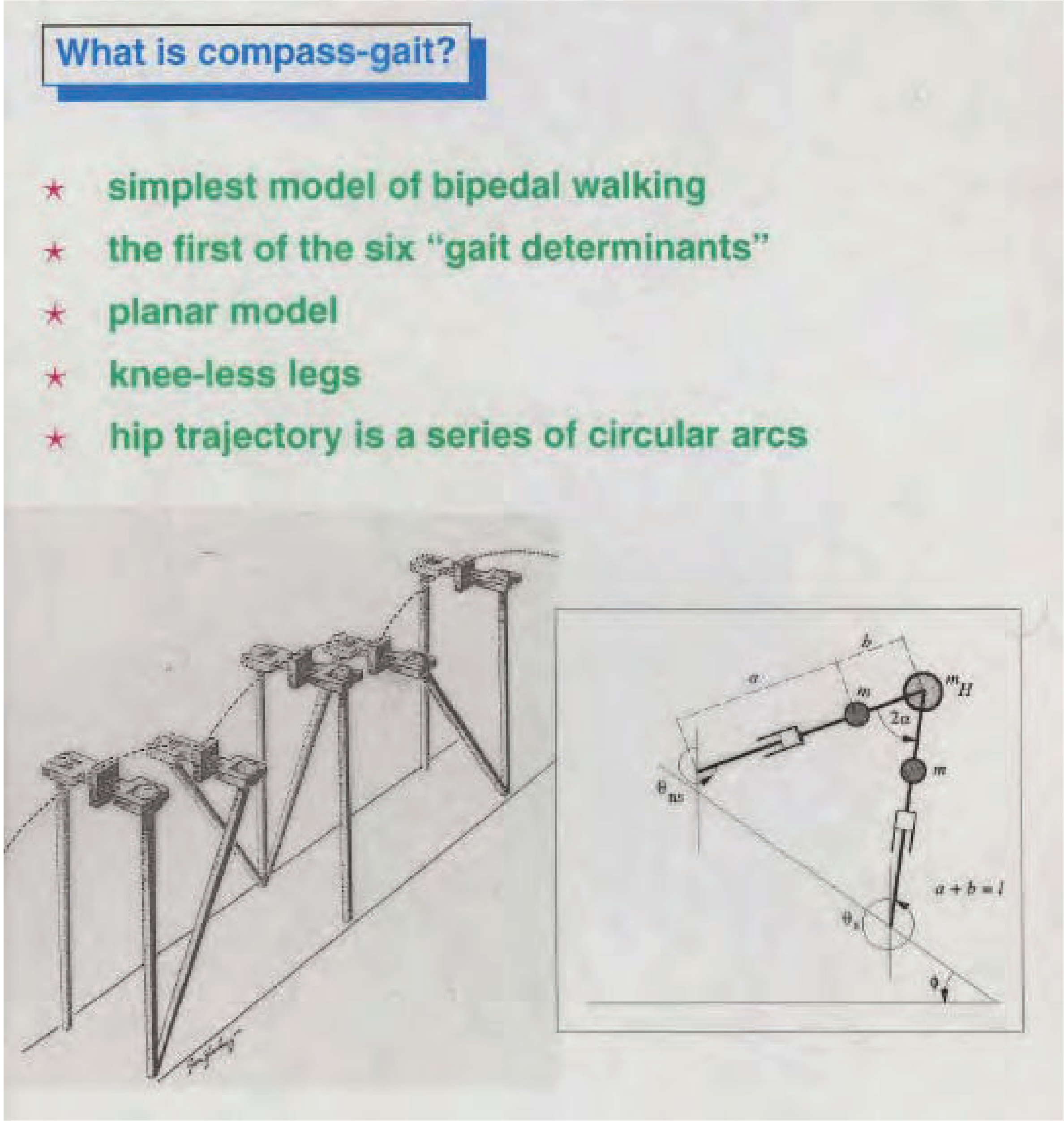
… and we will start with a passive robot called "compass gait robot".

- He gave me some handwritten notes.

What is compass gait?

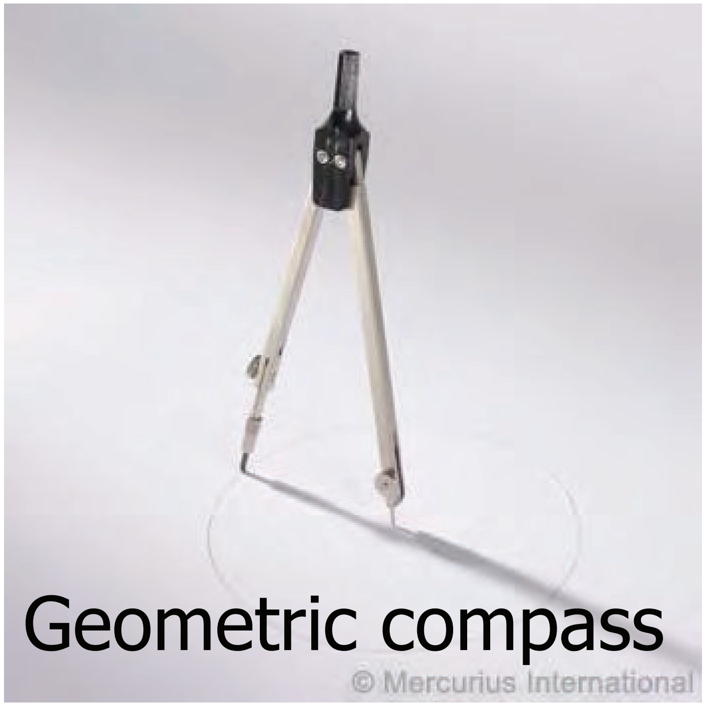
Passive Compass Gait

- What is compass gait and how did the name “originate”?
- Why is it important to study compass gait?
- What did we accomplish?
- What is going on in this field now?



What is compass-gait?

- simplest model of bipedal walking
- the first of the six "gait determinants"
- planar model
- knee-less legs
- hip trajectory is a series of circular arcs



Geometric compass

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Resurrection of study on "Compass Gait" Google References before and after Bernard's work (starting from 1993):

1950 – 1992: 29

1993 – 2012: 644

"compass gait"

About 29 results (0.05 sec)

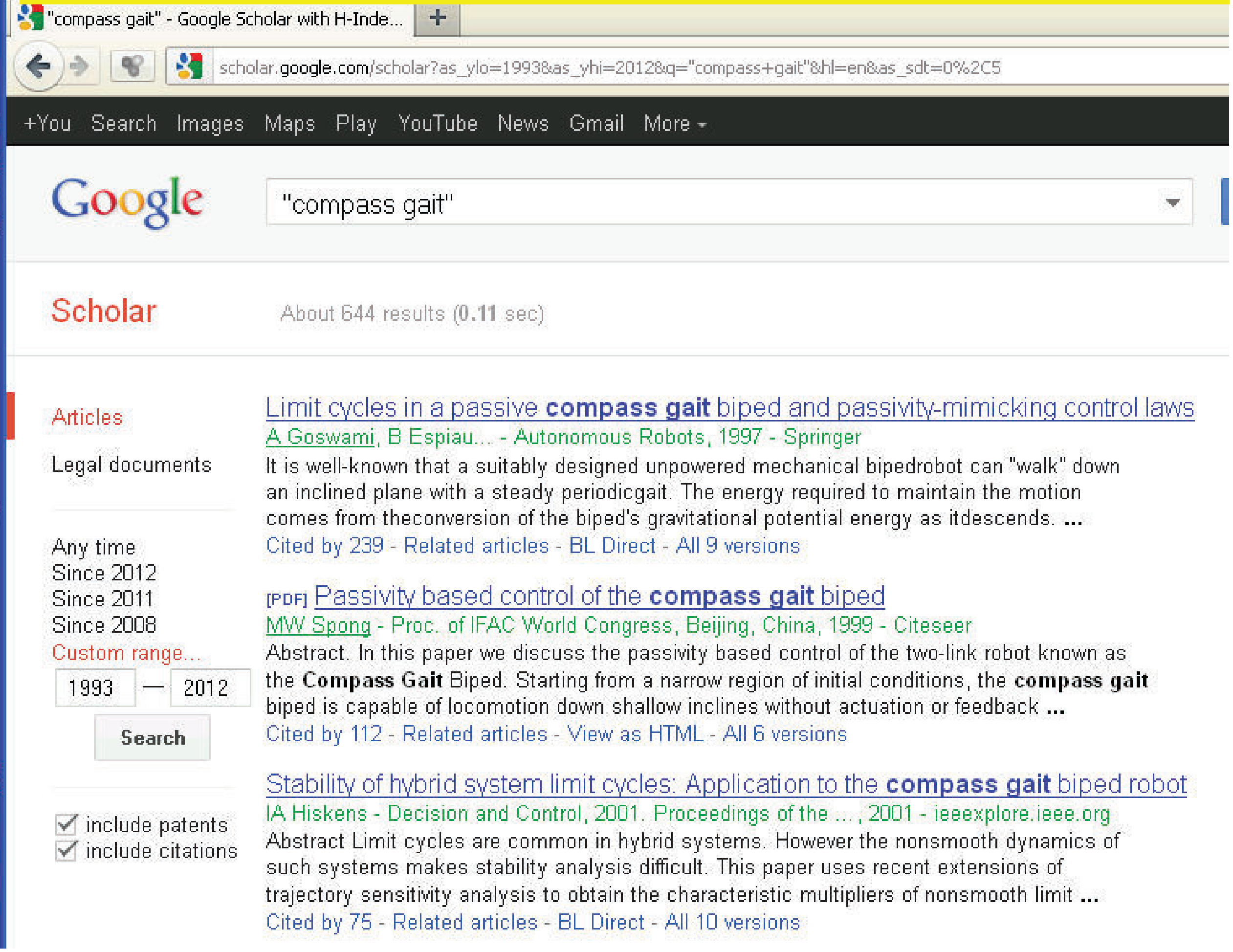
1950 — 1992

[BOOK] Muscles, reflexes, and locomotic
TA McMahon - 1984 - books.google.com
... De-afferented Spinal Walking 182 Feedforw
186 Problems 187 Chapter 8: Mechanics of L
of Walking and Running 190 Determinants of
Cited by 852 - Related articles - Library Searc

[CITATION] Design of realistic gaits for the
N Vasilonikolidakis... - Computer Animation,
Cited by 11 - Related articles - All 2 versions

Mechanics of locomotion
TA McMahon - The International Journal of Ro
... In this description, six determinants of nor
depends on a single degree of freedom in one
determined by the leg length. This is called c
Cited by 127 - Related articles - All 2 versions

☑ include patents
☑ include citations



"compass gait"

About 644 results (0.11 sec)

1993 — 2012

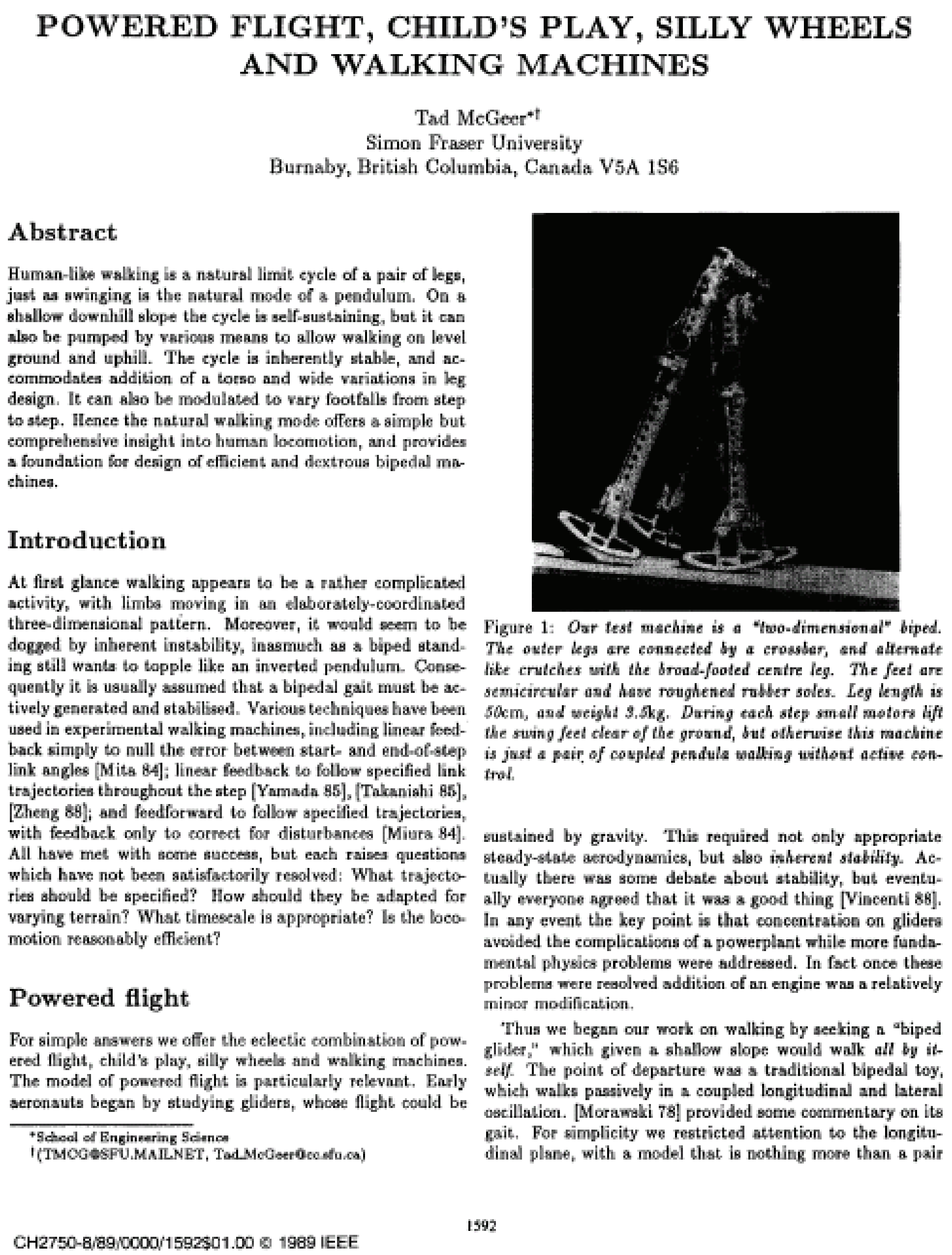
Limit cycles in a passive **compass gait** biped and passivity-mimicking control laws
A Goswami, B Espiau... - Autonomous Robots, 1997 - Springer
It is well-known that a suitably designed unpowered mechanical bipedrobot can "walk" down an inclined plane with a steady periodicgait. The energy required to maintain the motion comes from theconversion of the biped's gravitational potential energy as itdescends. ...
Cited by 239 - Related articles - BL Direct - All 9 versions

[PDF] Passivity based control of the **compass gait** biped
MW Spong - Proc. of IFAC World Congress, Beijing, China, 1999 - Citeseer
Abstract. In this paper we discuss the passivity based control of the two-link robot known as the **Compass Gait** Biped. Starting from a narrow region of initial conditions, the **compass gait** biped is capable of locomotion down shallow inclines without actuation or feedback ...
Cited by 112 - Related articles - View as HTML - All 6 versions

Stability of hybrid system limit cycles: Application to the **compass gait** biped robot
IA Hiskens - Decision and Control, 2001. Proceedings of the ..., 2001 - ieeexplore.ieee.org
Abstract Limit cycles are common in hybrid systems. However the nonsmooth dynamics of such systems makes stability analysis difficult. This paper uses recent extensions of trajectory sensitivity analysis to obtain the characteristic multipliers of nonsmooth limit ...
Cited by 75 - Related articles - BL Direct - All 10 versions

☑ include patents
☑ include citations

Tad McGeer, 1989



POWERED FLIGHT, CHILD'S PLAY, SILLY WHEELS AND WALKING MACHINES

Tad McGeer[*,†]
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Burnaby, British Columbia, Canada V5A 1S6

Abstract

Human-like walking is a natural limit cycle of a pair of legs, just as swinging is the natural mode of a pendulum. On a shallow downhill slope the cycle is self-sustaining, but it can also be pumped by various means to allow walking on level ground and uphill. The cycle is inherently stable, and accommodates addition of a torso and wide variations in leg design. It can also be modulated to vary footfalls from step to step. Hence the natural walking mode offers a simple but comprehensive insight into human locomotion, and provides a foundation for design of efficient and dextrous bipedal machines.

Introduction

At first glance walking appears to be a rather complicated activity, with limbs moving in an elaborately-coordinated three-dimensional pattern. Moreover, it would seem to be dogged by inherent instability, inasmuch as a biped standing still wants to topple like an inverted pendulum. Consequently it is usually assumed that a bipedal gait must be actively generated and stabilised. Various techniques have been used in experimental walking machines, including linear feedback simply to null the error between start- and end-of-step link angles [Mita 84]; linear feedback to follow specified link trajectories throughout the step [Yamada 85], [Takanishi 85], [Zheng 88]; and feedforward to follow specified trajectories, with feedback only to correct for disturbances [Miura 84]. All have met with some success, but each raises questions which have not been satisfactorily resolved: What trajectories should be specified? How should they be adapted for varying terrain? What timescale is appropriate? Is the locomotion reasonably efficient?

Powered flight

For simple answers we offer the eclectic combination of powered flight, child's play, silly wheels and walking machines. The model of powered flight is particularly relevant. Early aeronauts began by studying gliders, whose flight could be sustained by gravity. This required not only appropriate steady-state aerodynamics, but also *inherent stability*. Actually there was some debate about stability, but eventually everyone agreed that it was a good thing [Vincenti 88]. In any event the key point is that concentration on gliders avoided the complications of a powerplant while more fundamental physics problems were addressed. In fact once these problems were resolved addition of an engine was a relatively minor modification.

Thus we began our work on walking by seeking a "biped glider," which given a shallow slope would walk *all by itself.* The point of departure was a traditional bipedal toy, which walks passively in a coupled longitudinal and lateral oscillation. [Morawski 78] provided some commentary on its gait. For simplicity we restricted attention to the longitudinal plane, with a model that is nothing more than a pair

Figure 1: *Our test machine is a "two-dimensional" biped. The outer legs are connected by a crossbar, and alternate like crutches with the broad-footed centre leg. The feet are semicircular and have roughened rubber soles. Leg length is 50cm, and weight 3.5kg. During each step small motors lift the swing feet clear of the ground, but otherwise this machine is just a pair of coupled pendula walking without active control.*

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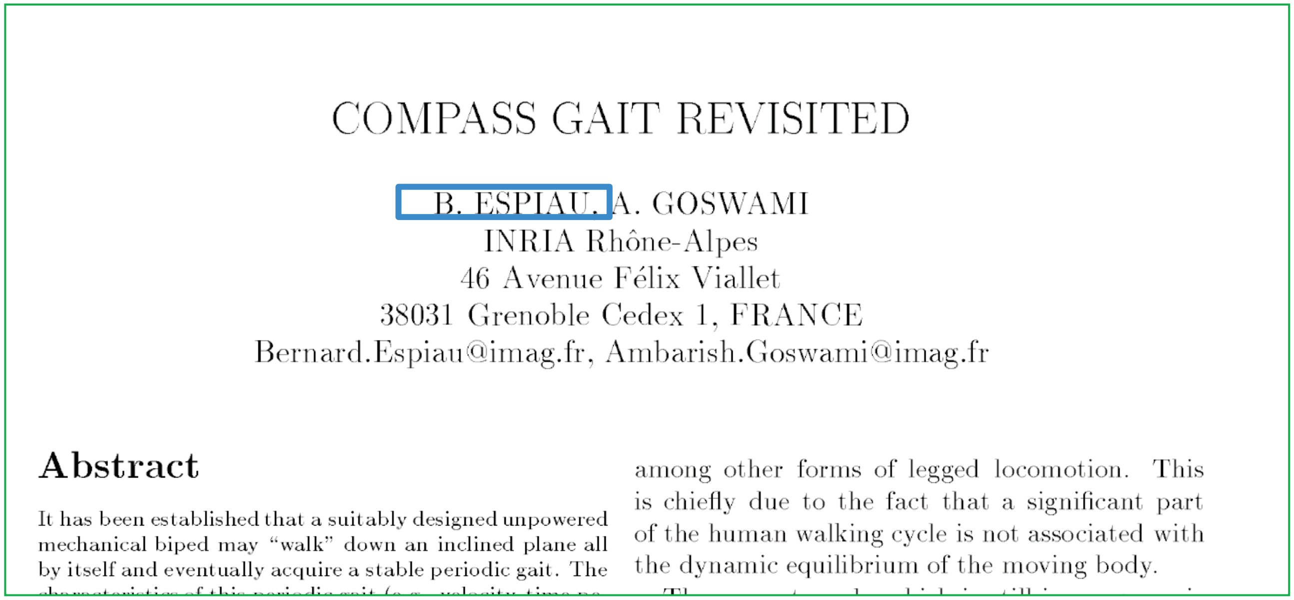
Compass Gait (1993-1997)



COMPASS GAIT REVISITED

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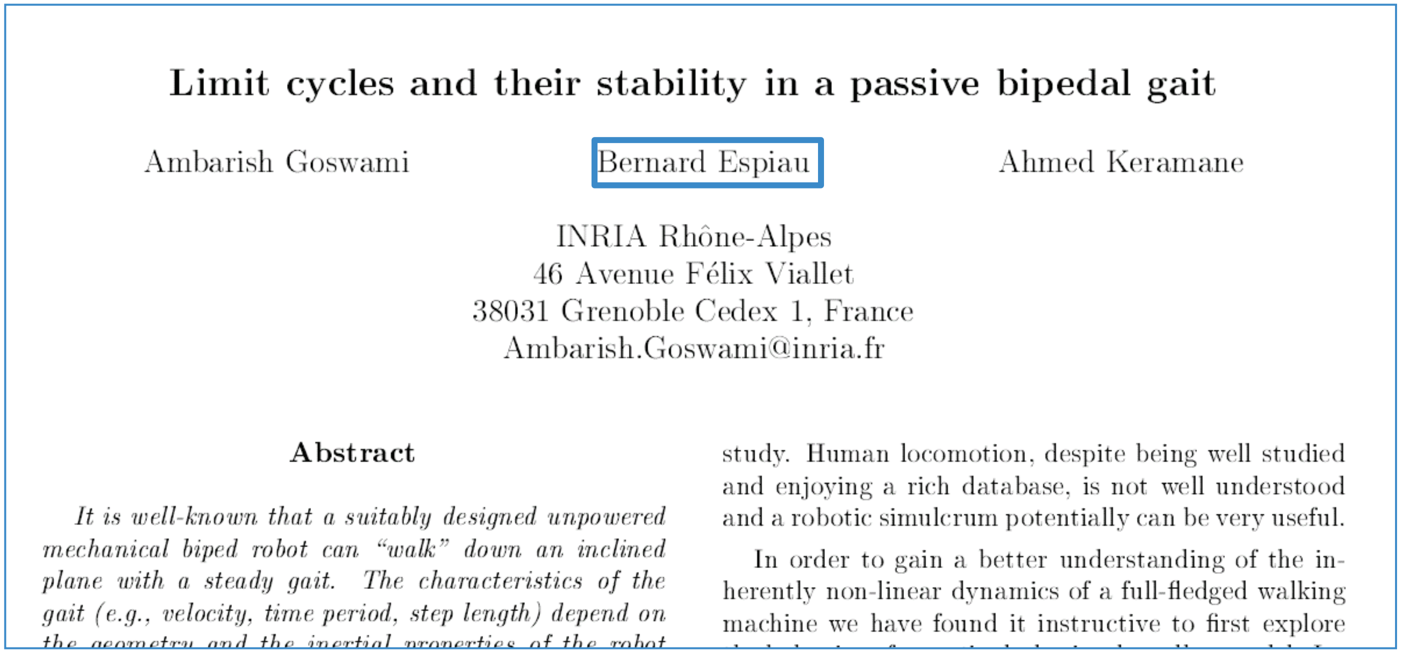
Abstract

It has been established that a suitably designed unpowered mechanical biped may "walk" down an inclined plane all by itself and eventually acquire a stable periodic gait. The

among other forms of legged locomotion. This is chiefly due to the fact that a significant part of the human walking cycle is not associated with the dynamic equilibrium of the moving body.

SyRoCo 1994
(29)

Google scholar citations in parentheses



Limit cycles and their stability in a passive bipedal gait

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Abstract

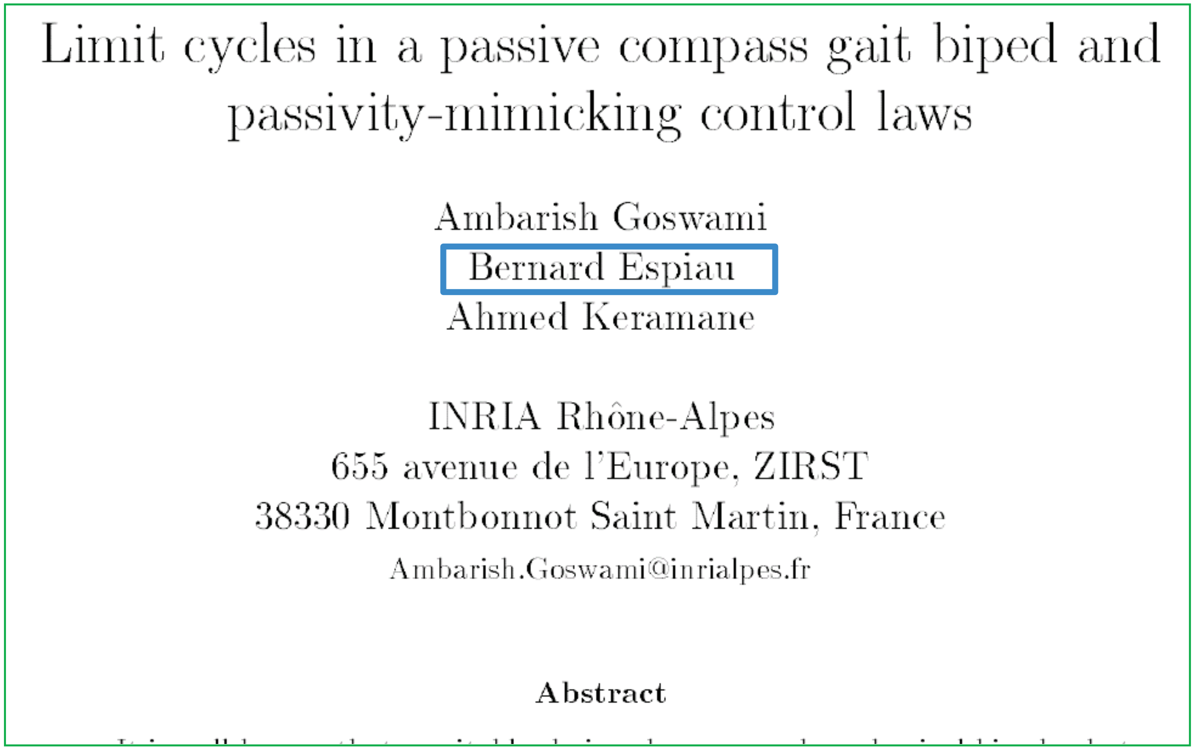
It is well-known that a suitably designed unpowered mechanical biped robot can "walk" down an inclined plane with a steady gait. The characteristics of the gait (e.g., velocity, time period, step length) depend on

study. Human locomotion, despite being well studied and enjoying a rich database, is not well understood and a robotic simulcrum potentially can be very useful.

In order to gain a better understanding of the inherently non-linear dynamics of a full-fledged walking machine we have found it instructive to first explore

ICRA 1996
(158)

Compass Gait (1993-1997)



Limit cycles in a passive compass gait biped and passivity-mimicking control laws

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Bernard Espiau
Ahmed Keramane

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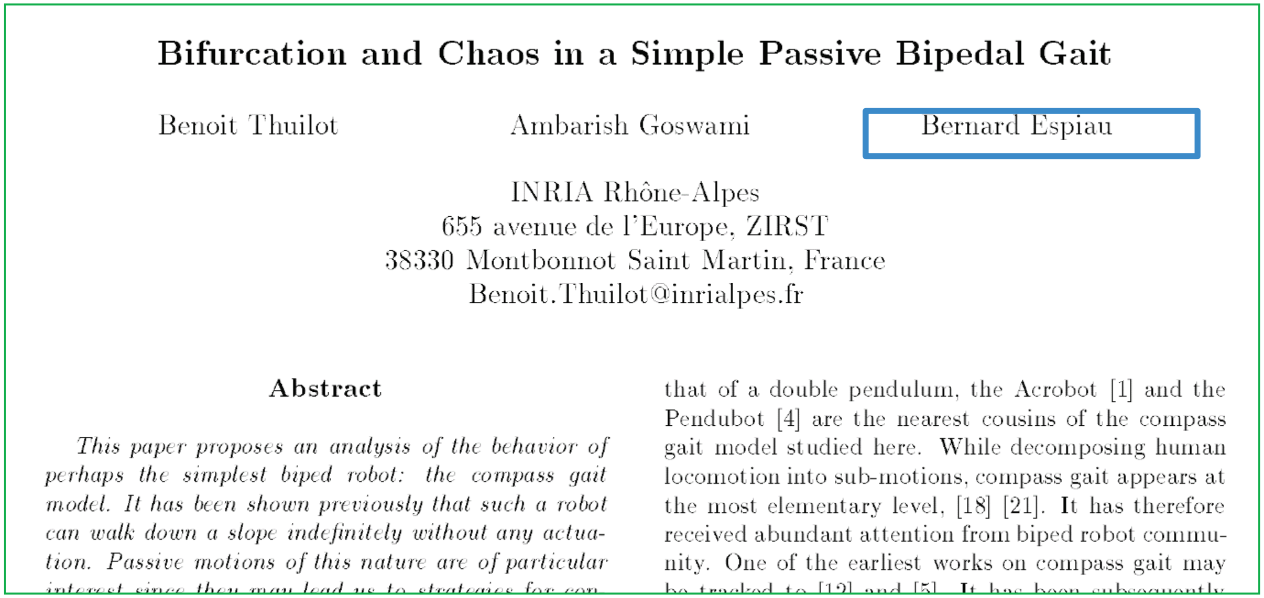
Ambarish.Goswami@inrialpes.fr

Abstract

Journal of
Autonomous Robots 1997
(239)



Bifurcation and Chaos in a Simple Passive Bipedal Gait

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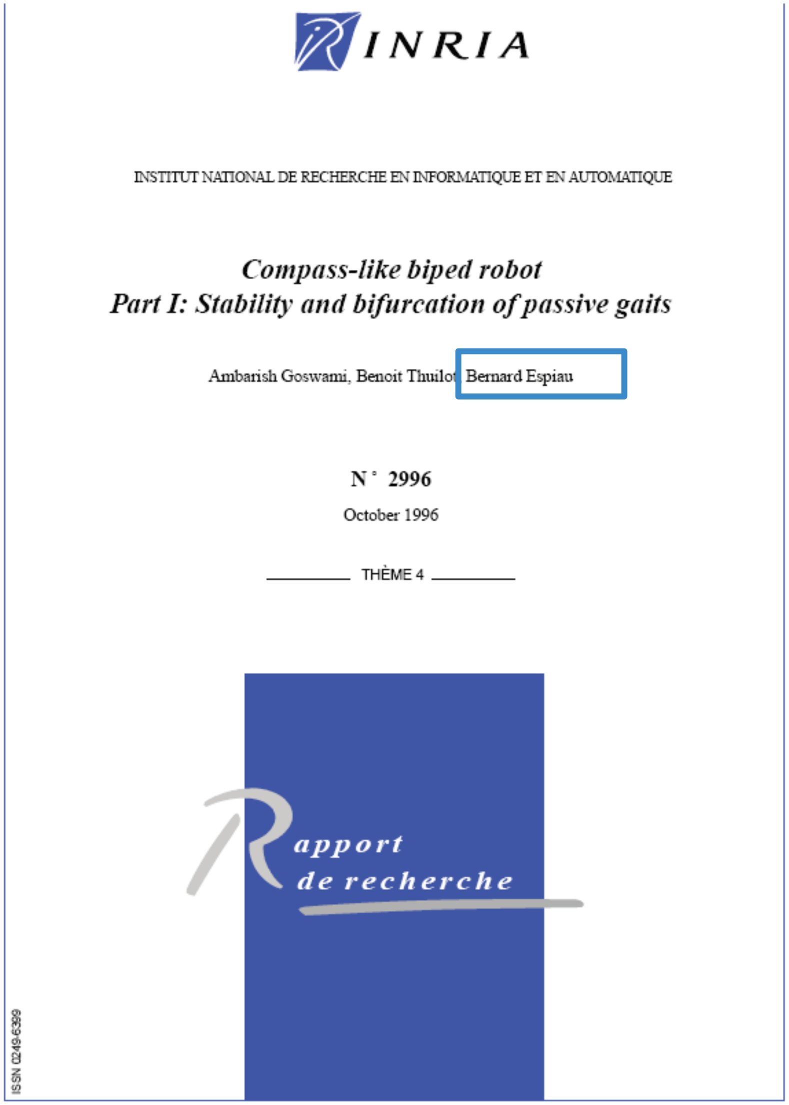
Abstract

This paper proposes an analysis of the behavior of perhaps the simplest biped robot: the compass gait model. It has been shown previously that such a robot can walk down a slope indefinitely without any actuation. Passive motions of this nature are of particular

that of a double pendulum, the Acrobot [1] and the Pendubot [4] are the nearest cousins of the compass gait model studied here. While decomposing human locomotion into sub-motions, compass gait appears at the most elementary level, [18] [21]. It has therefore received abundant attention from biped robot community. One of the earliest works on compass gait may

ICRA 1997
(59)

Compass Gait (1993-1997)



INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Compass-like biped robot
Part I: Stability and bifurcation of passive gaits

Ambarish Goswami, Benoit Thuilot, Bernard Espiau

N° 2996

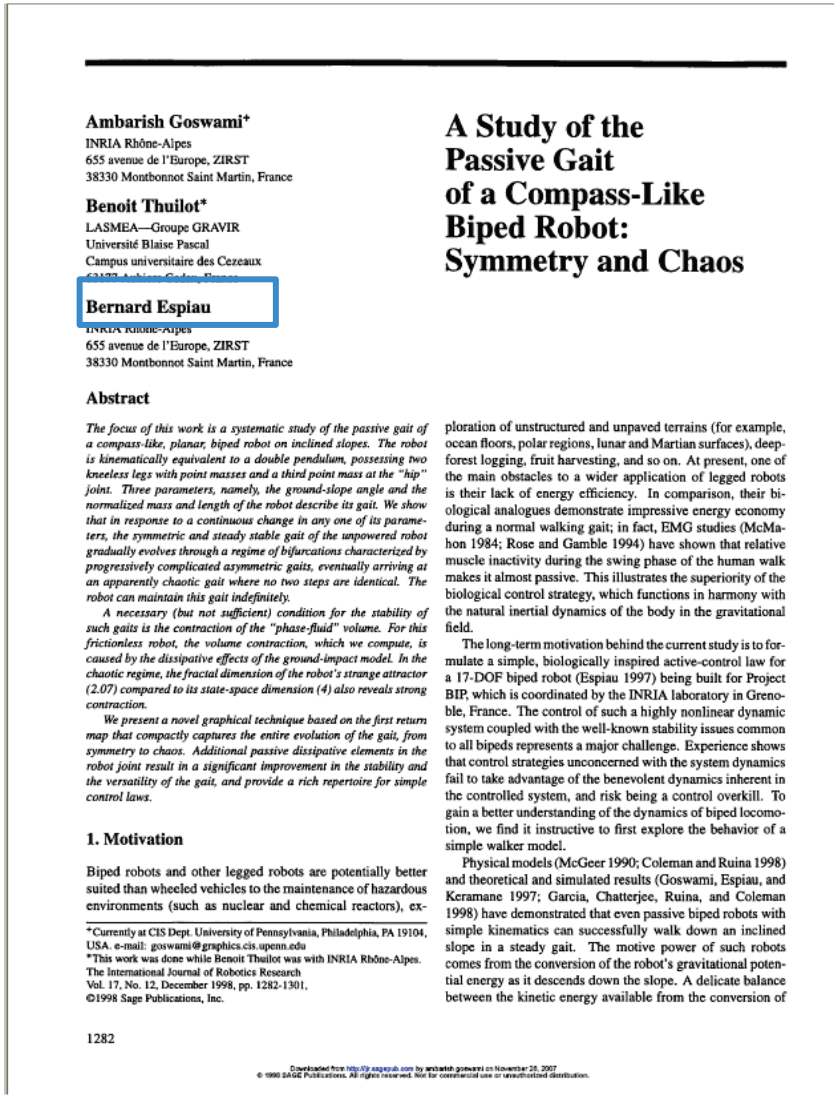
October 1996

THÈME 4

Rapport de recherche

ISSN 0249-6399

INRIA Report 1996 (178)



A Study of the Passive Gait of a Compass-Like Biped Robot: Symmetry and Chaos

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Abstract

The focus of this work is a systematic study of the passive gait of a compass-like, planar, biped robot on inclined slopes. The robot is kinematically equivalent to a double pendulum, possessing two kneeless legs with point masses and a third point mass at the "hip" joint. Three parameters, namely, the ground-slope angle and the normalized mass and length of the robot describe its gait. We show that in response to a continuous change in any one of its parameters, the symmetric and steady stable gait of the unpowered robot gradually evolves through a regime of bifurcations characterized by progressively complicated asymmetric gaits, eventually arriving at an apparently chaotic gait where no two steps are identical. The robot can maintain this gait indefinitely.

A necessary (but not sufficient) condition for the stability of such gaits is the contraction of the "phase-fluid" volume. For this frictionless robot, the volume contraction, which we compute, is caused by the dissipative effects of the ground-impact model. In the chaotic regime, the fractal dimension of the robot's strange attractor (2.07) compared to its state-space dimension (4) also reveals strong contraction.

We present a novel graphical technique based on the first return map that compactly captures the entire evolution of the gait, from symmetry to chaos. Additional passive dissipative elements in the robot joint result in a significant improvement in the stability and the versatility of the gait, and provide a rich repertoire for simple control laws.

1. Motivation

Biped robots and other legged robots are potentially better suited than wheeled vehicles to the maintenance of hazardous environments (such as nuclear and chemical reactors), exploration of unstructured and unpaved terrains (for example, ocean floors, polar regions, lunar and Martian surfaces), deep-forest logging, fruit harvesting, and so on. At present, one of the main obstacles to a wider application of legged robots is their lack of energy efficiency. In comparison, their biological analogues demonstrate impressive energy economy during a normal walking gait; in fact, EMG studies (McMahon 1984; Rose and Gamble 1994) have shown that relative muscle inactivity during the swing phase of the human walk makes it almost passive. This illustrates the superiority of the biological control strategy, which functions in harmony with the natural inertial dynamics of the body in the gravitational field.

The long-term motivation behind the current study is to formulate a simple, biologically inspired active-control law for a 17-DOF biped robot (Espiau 1997) being built for Project BIP, which is coordinated by the INRIA laboratory in Grenoble, France. The control of such a highly nonlinear dynamic system coupled with the well-known stability issues common to all bipeds represents a major challenge. Experience shows that control strategies unconcerned with the system dynamics fail to take advantage of the benevolent dynamics inherent in the controlled system, and risk being a control overkill. To gain a better understanding of the dynamics of biped locomotion, we find it instructive to first explore the behavior of a simple walker model.

Physical models (McGeer 1990; Coleman and Ruina 1998) and theoretical and simulated results (Goswami, Espiau, and Keramane 1997; Garcia, Chatterjee, Ruina, and Coleman 1998) have demonstrated that even passive biped robots with simple kinematics can successfully walk down an inclined slope in a steady gait. The motive power of such robots comes from the conversion of the robot's gravitational potential energy as it descends down the slope. A delicate balance between the kinetic energy available from the conversion of

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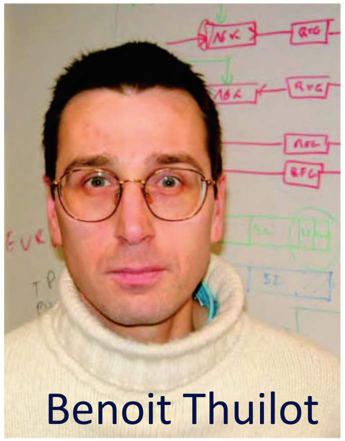
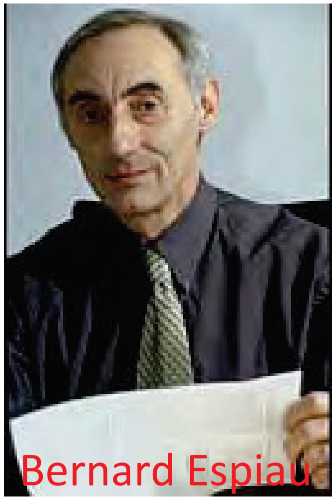
*This work was done while Benoit Thuilot was with INRIA Rhône-Alpes.

The International Journal of Robotics Research
Vol. 17, No. 12, December 1998, pp. 1282-1301,

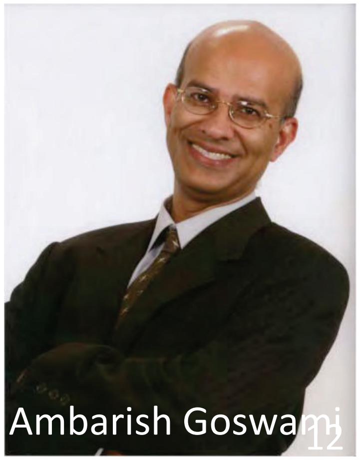
IJRR 1998 (278)



Benoit Thuilot



Bernard Espiau



Ambarish Goswami

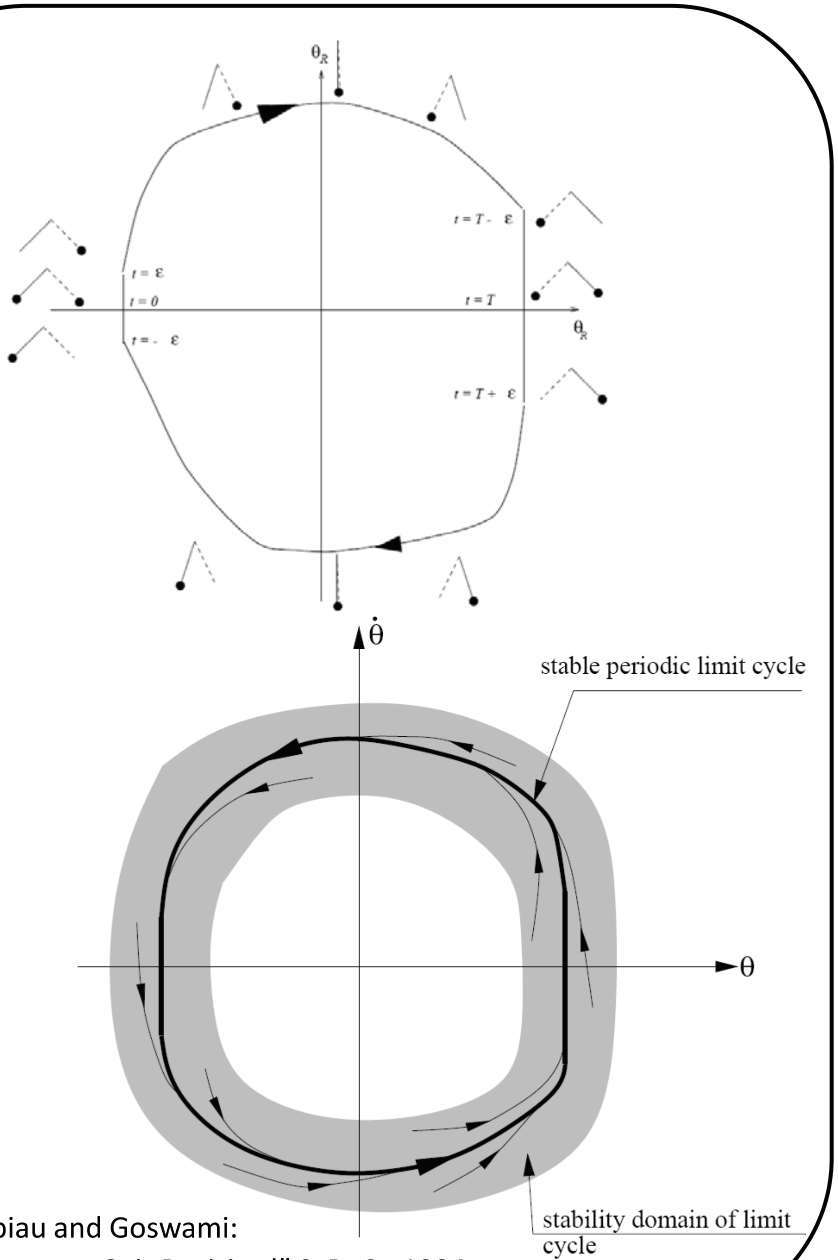
MOTIVATION (Why study passive gait?)

- study the fundamentals of gait dynamics
- understand the principal nonlinearities of the uncontrolled locomotion system, ballistic walking
- learn to use *minimal* control, in harmony with the inherent system dynamics
- explore relationship to minimum energy gait
- explore relationship to hybrid continuous-discrete mechanical systems

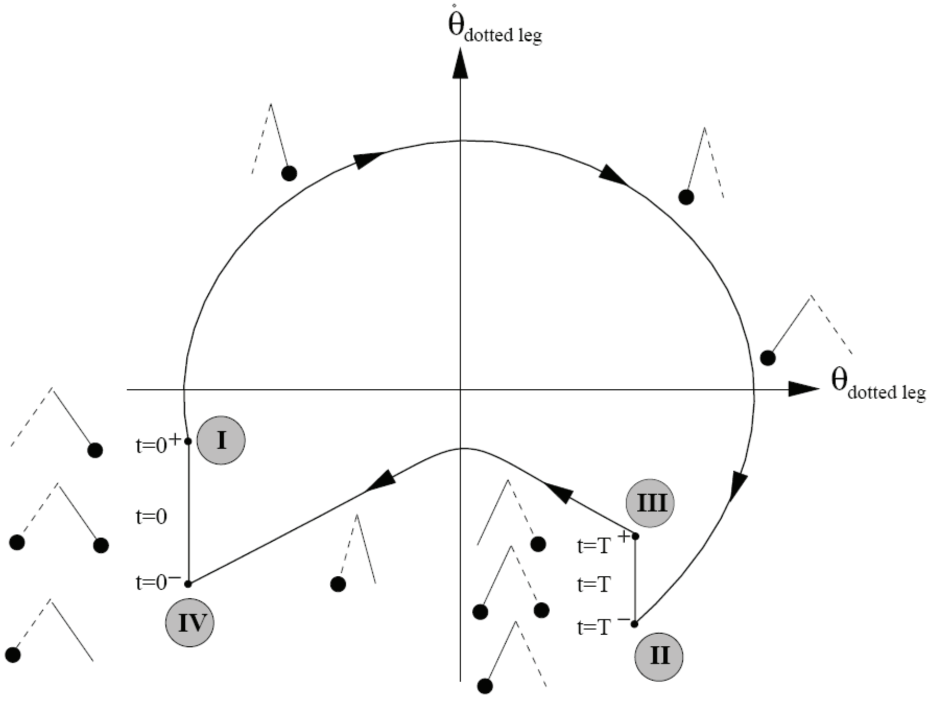
To remember:

- a passive biped robot is not a machine of practical utility (no actuation, no use)
- true compass-gait robot will have foot-scuffing problem

Early results: Intuitive -> Exact

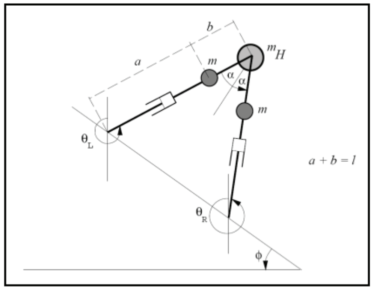


Espiau and Goswami:
“Compass Gait Revisited” SyRoCo 1994

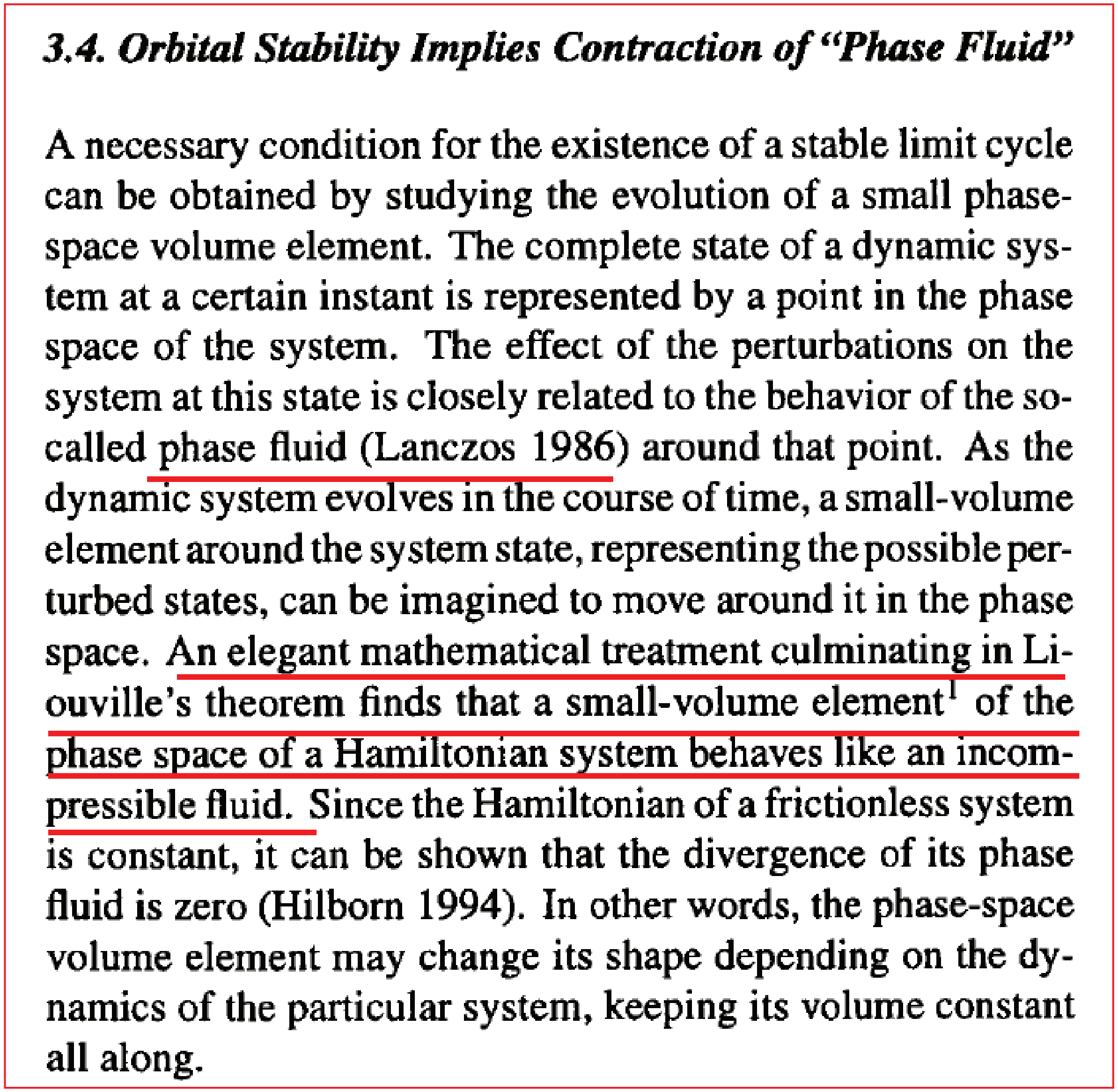


Compass Gait Limit Cycle,
(JAR 1997, IJRR 1999)
(Orbital stability)

Stability and "phase fluid"

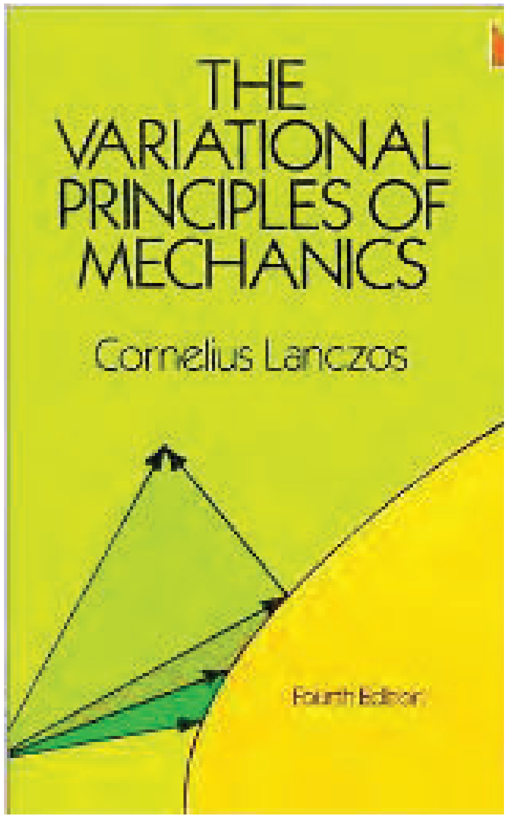


(IJRR 1998)



3.4. Orbital Stability Implies Contraction of "Phase Fluid"

A necessary condition for the existence of a stable limit cycle can be obtained by studying the evolution of a small phase-space volume element. The complete state of a dynamic system at a certain instant is represented by a point in the phase space of the system. The effect of the perturbations on the system at this state is closely related to the behavior of the so-called phase fluid (Lanczos 1986) around that point. As the dynamic system evolves in the course of time, a small-volume element around the system state, representing the possible perturbed states, can be imagined to move around it in the phase space. An elegant mathematical treatment culminating in Liouville's theorem finds that a small-volume element[1] of the phase space of a Hamiltonian system behaves like an incompressible fluid. Since the Hamiltonian of a frictionless system is constant, it can be shown that the divergence of its phase fluid is zero (Hilborn 1994). In other words, the phase-space volume element may change its shape depending on the dynamics of the particular system, keeping its volume constant all along.



THE
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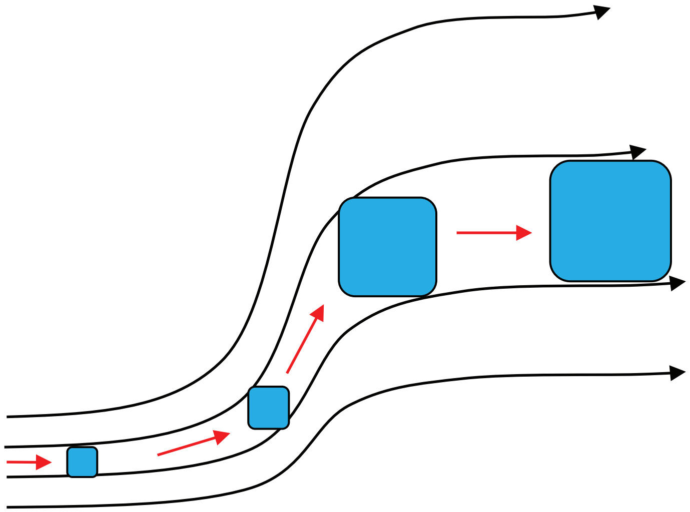
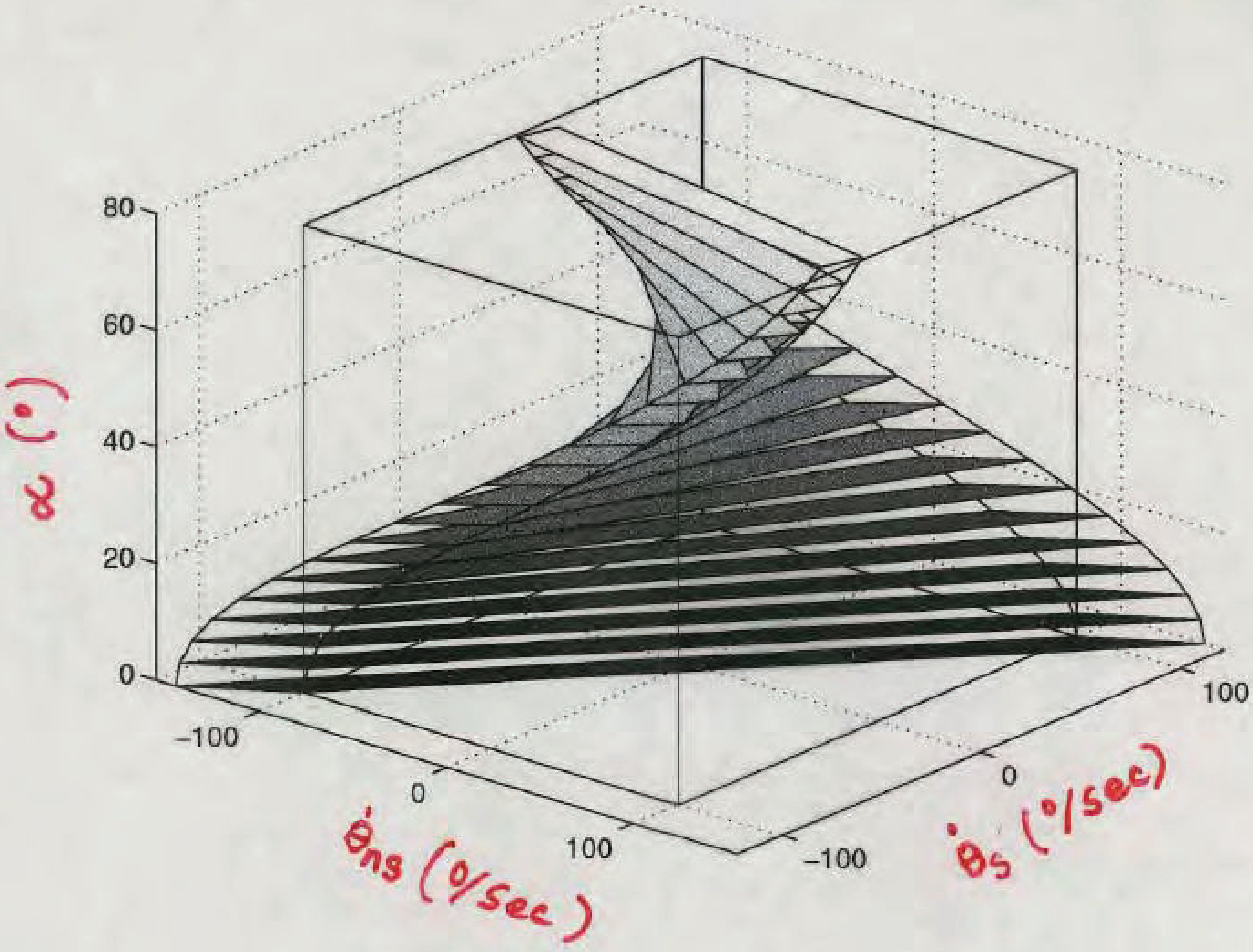
PRINCIPLES OF
MECHANICS

Cornelius Lanczos

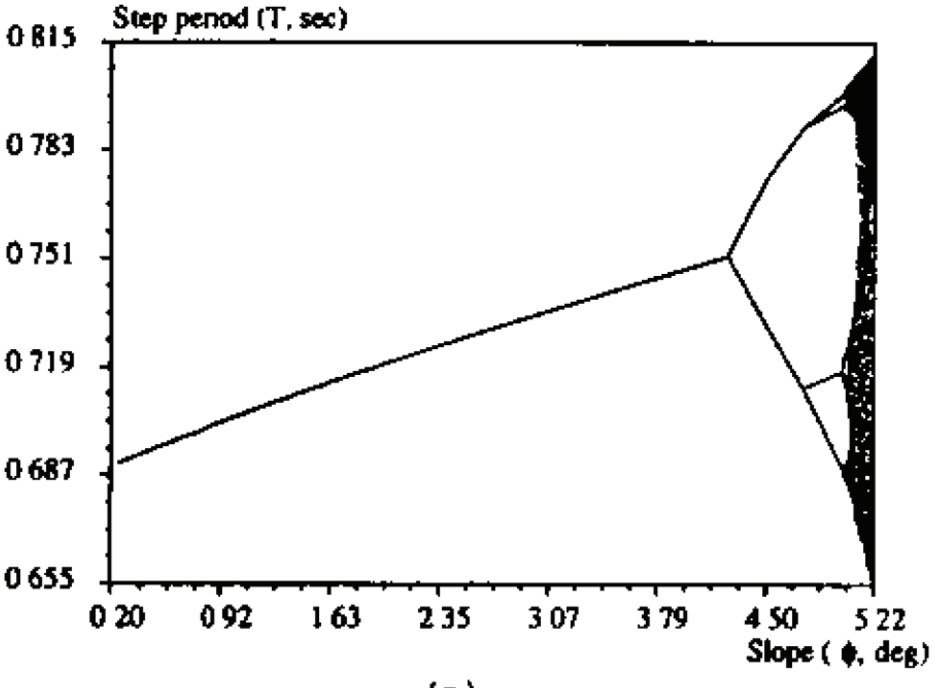
Fourth Edition

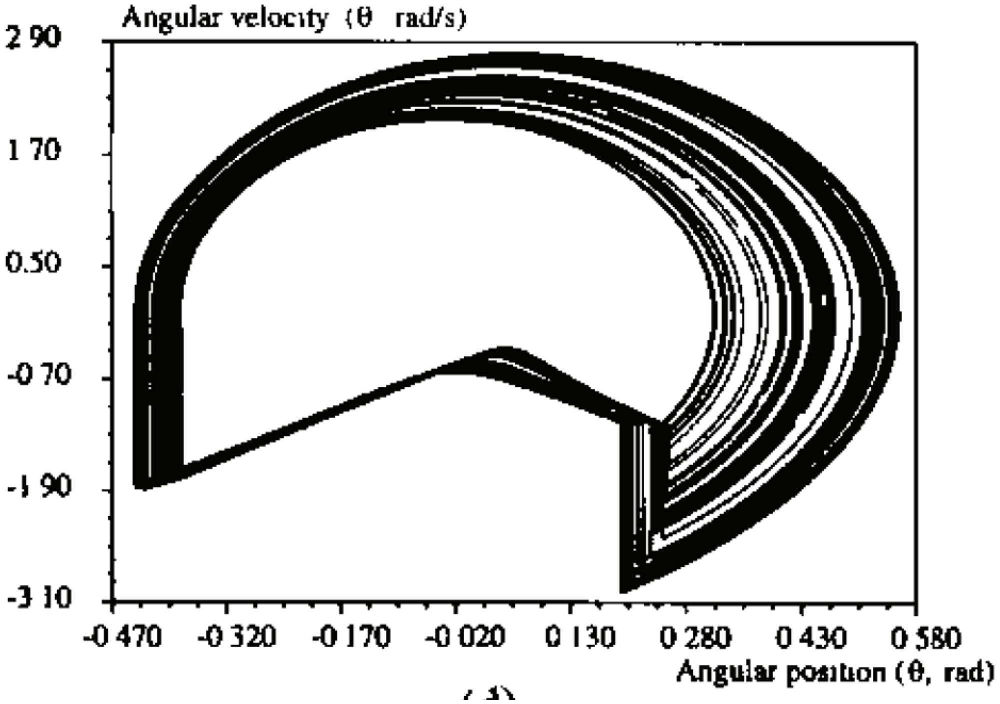


Transition matrix and "phase fluid" contraction



Period doubling, chaos and bifurcation in compass gait

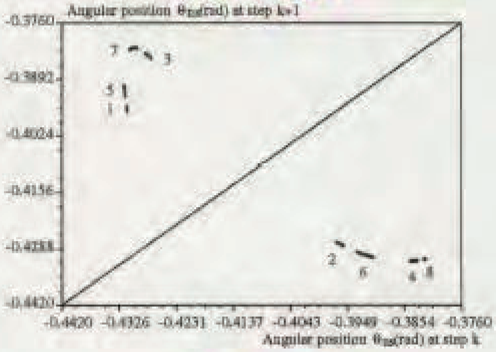




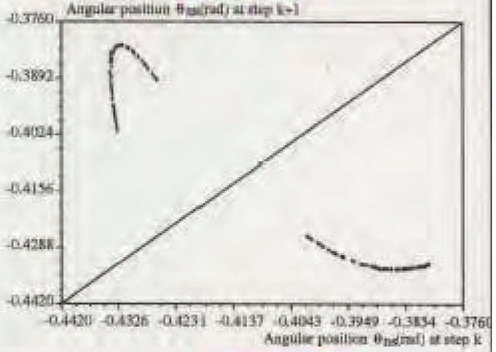
(Concurrent work by Ruina’s group at Cornell University, who shared proposal preprints with us!)

Transition to chaos – evolution of first return map

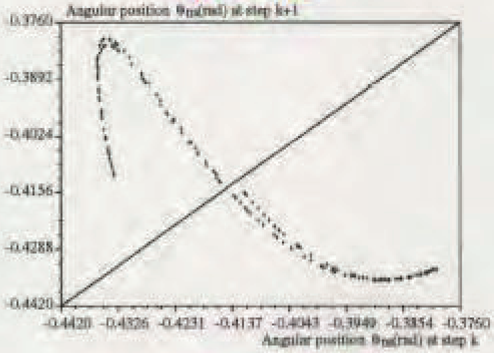
$\phi = 5.04^\circ$



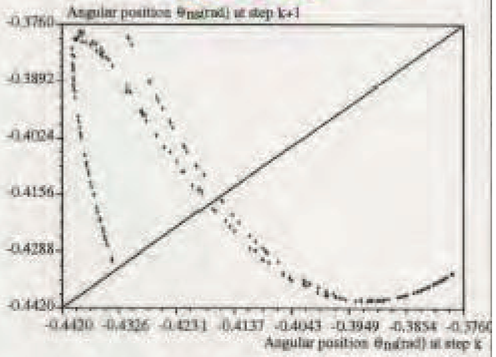
$\phi = 5.08^\circ$



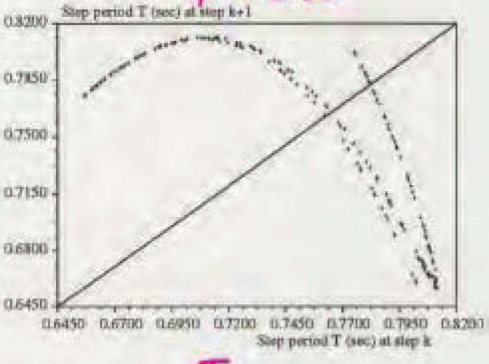
$\phi = 5.12^\circ$



$\phi = 5.20^\circ$



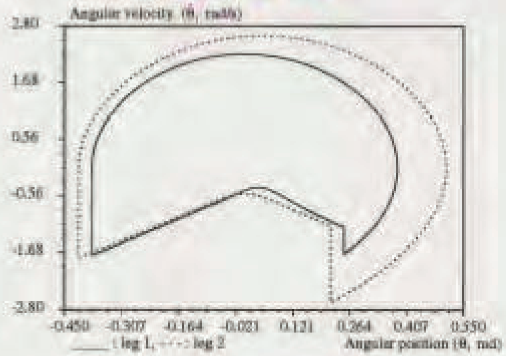
$\phi = 5.20^\circ$



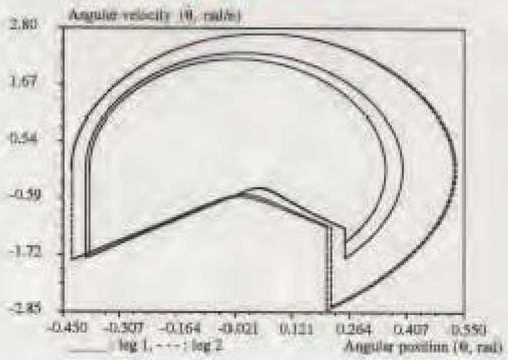
T

Evolution of limit cycles

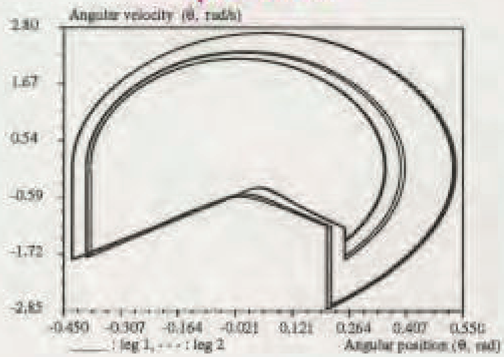
$\phi = 4.75^\circ$



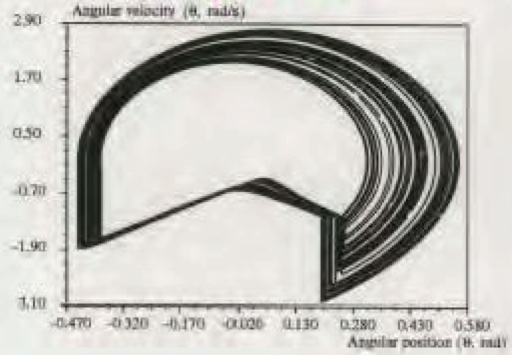
$\phi = 5.0^\circ$



$\phi = 5.02^\circ$

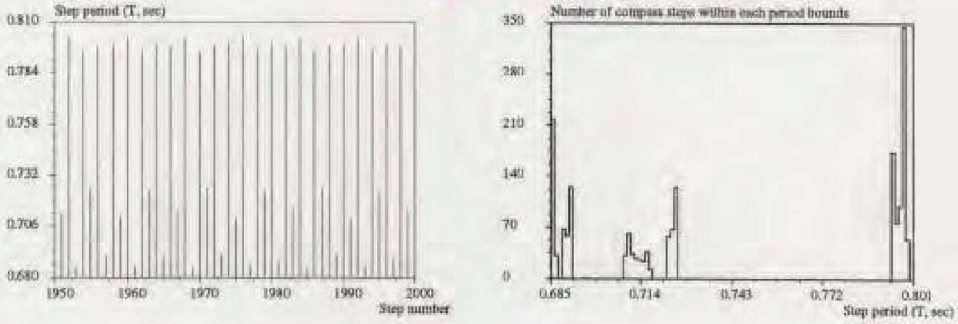


$\phi = 5.20^\circ$

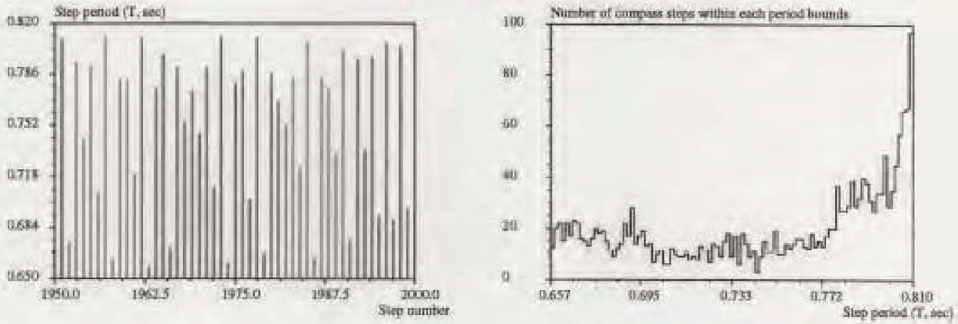


Transition to chaos - study of step period

$\phi = 5.04^\circ$



$\phi = 5.20^\circ$



BROAD BAND
FREQUENCY SPECTRUM

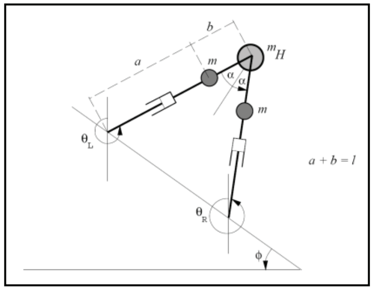
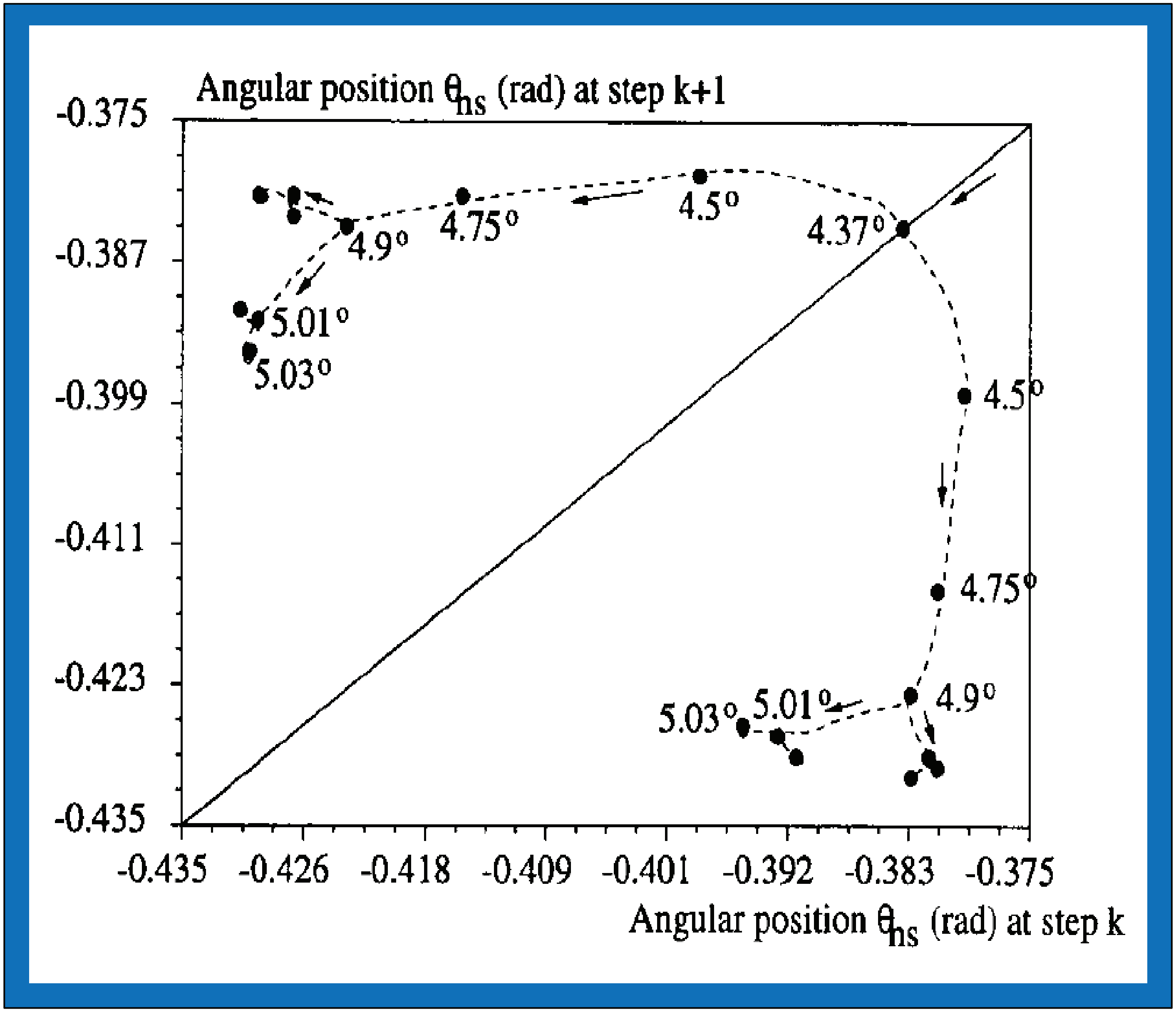
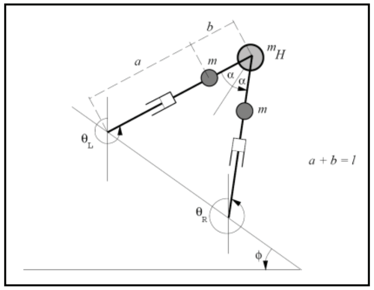


Chart of successive bifurcations

(IJRR 1998)





Dampers improve gait stability

(IJRR 1998)

5. Dampers Improve Gait Stability

Dramatically!!

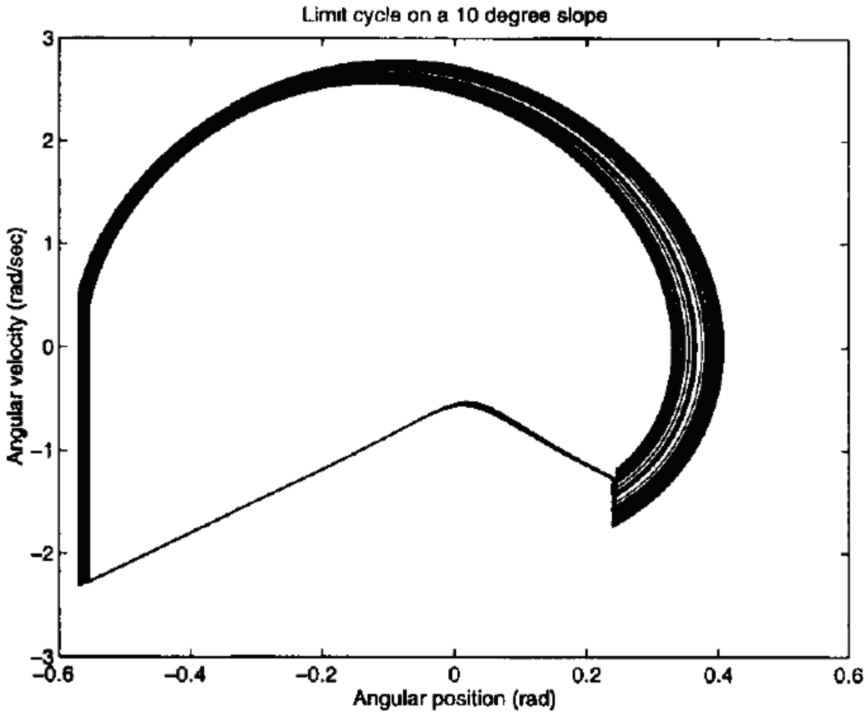


Fig. 17. The phase diagram of the compass robot with a pass quadratic hip damper (with a coefficient 0.23 Nm/(rad/sec walking down a 10° slope with a steady gait.

Taking a cue from the connection between gait stability and energy dissipation, we studied the effect of placing passive damping elements in the robot's hip joint. A significant improvement of the gait stability and overall gait versatility was achieved by this without violating the "passive" status of the robot. The damper affects a continuous dissipation of energy in the robot in addition to the energy dissipated intermittently during ground impact. Although even a linear damper may increase the range of slopes on which steady gaits exist, we obtained more encouraging results with quadratic dampers.

Finally, let us mention that the addition of a quadratic damper $\propto (\theta_{ns})^2$ dramatically influences the robot's behavior. With this damper in action, the robot can possess extremely large limit-cycle attraction basins and can deal with steep slopes (we have found steady gaits up to 20°) that are impossible otherwise. The implications of this are unclear, and the implementation of such a damper (either passively or actively) is, at least, not straightforward.

Unknowns of Compass Gait

- Is it true that there is **only one passive limit cycle** for a given slope? If so, why?

- **Existence of limit cycle**: there are three energy quantities that determine the gait,
  a) PE lost due to descent,
  b) KE gained
  c) KE lost due to impact.
- These are the necessary conditions. What are the sufficient conditions?

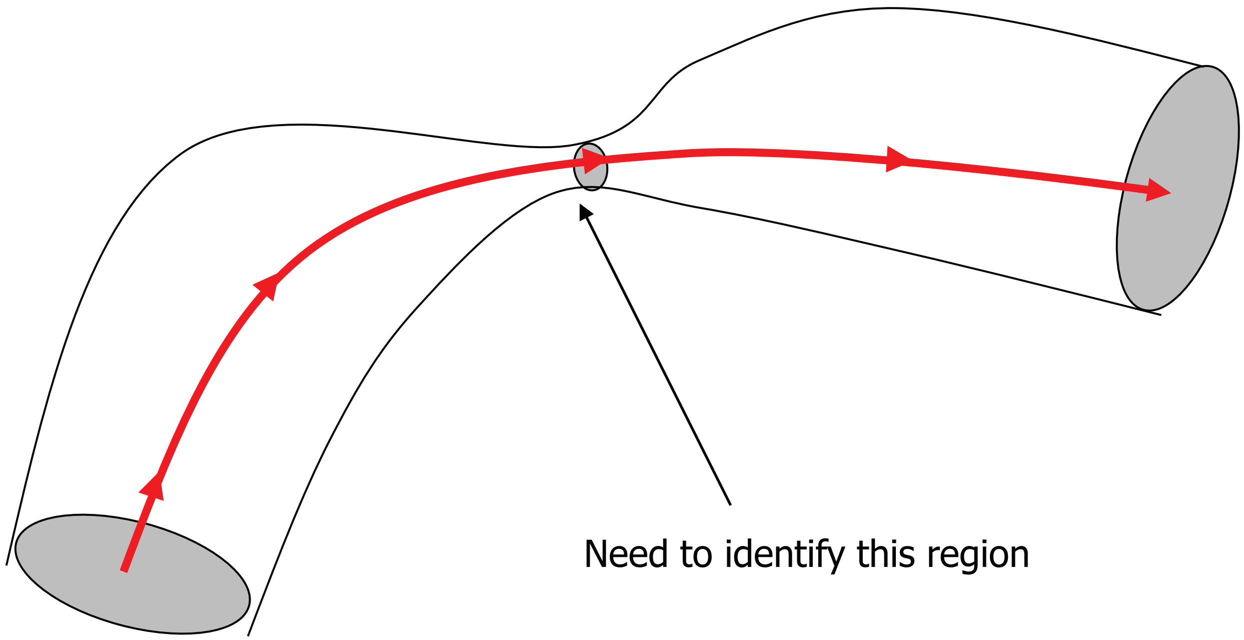
- Even when we know there is a limit cycle why is it so hard to find it?

- Integrate springs and dampers to compass gait and search for passive limit cycles

- Investigate the impact model. Has anyone tried to verify this experimentally?

Unknowns of Compass Gait

- What is the basin boundary of a limit cycle (both for state perturbation and parameter perturbation)



- Are there fundamental differences between effects of state error and parameter error?
- Size of basin of attraction seems to be much larger along the direction of the velocity states than that along the position states, similar behavior observed in other hybrid systems. What is the explanation?
- Two different stability characteristic: Size of attraction basin and strength of contraction
- Chaos and bifurcation are observed in passive gait – so what?

Work continued by others…

Prof. Fumihiko Asano
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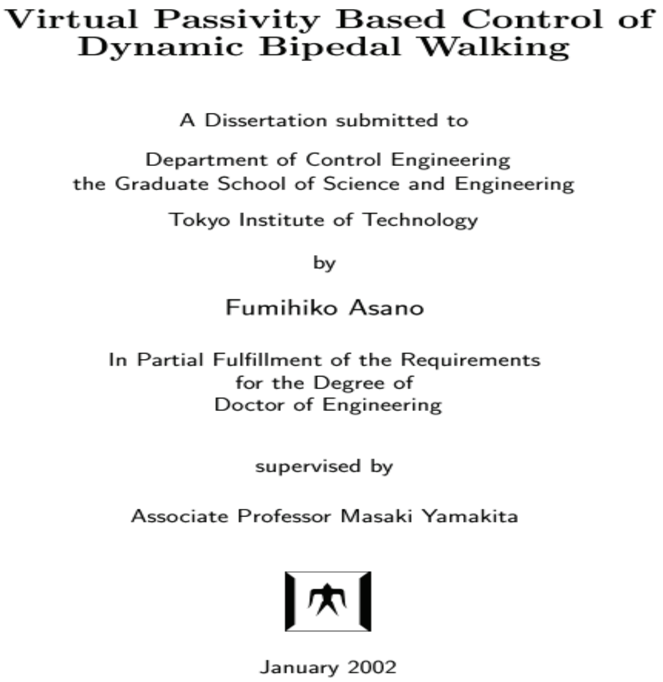


Virtual Passivity Based Control of Dynamic Bipedal Walking

A Dissertation submitted to

Department of Control Engineering
the Graduate School of Science and Engineering

Tokyo Institute of Technology

by

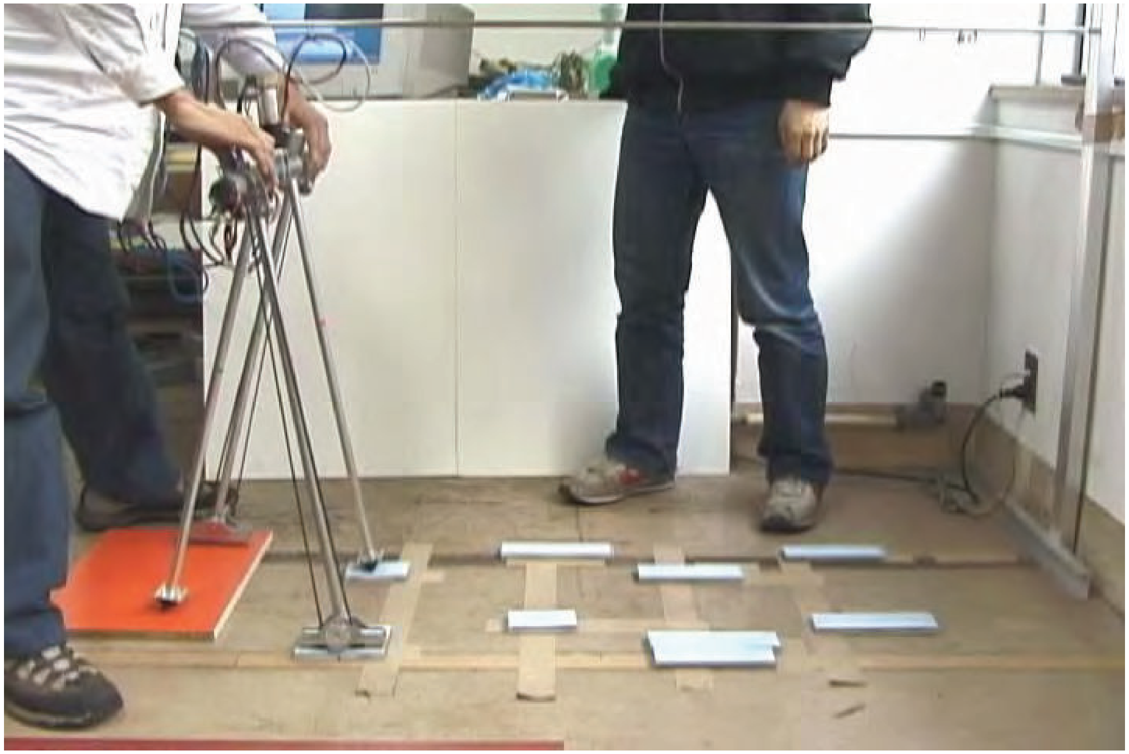
Fumihiko Asano

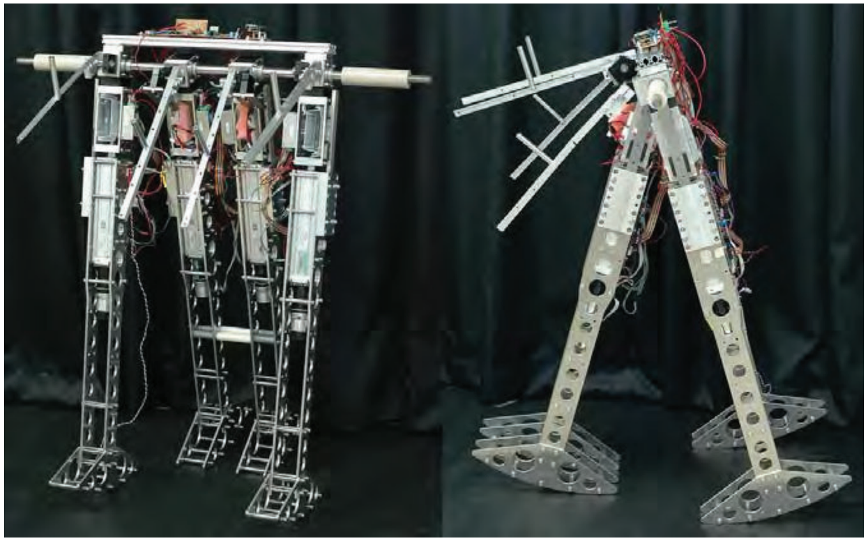
In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Engineering

supervised by

Associate Professor Masaki Yamakita

January 2002





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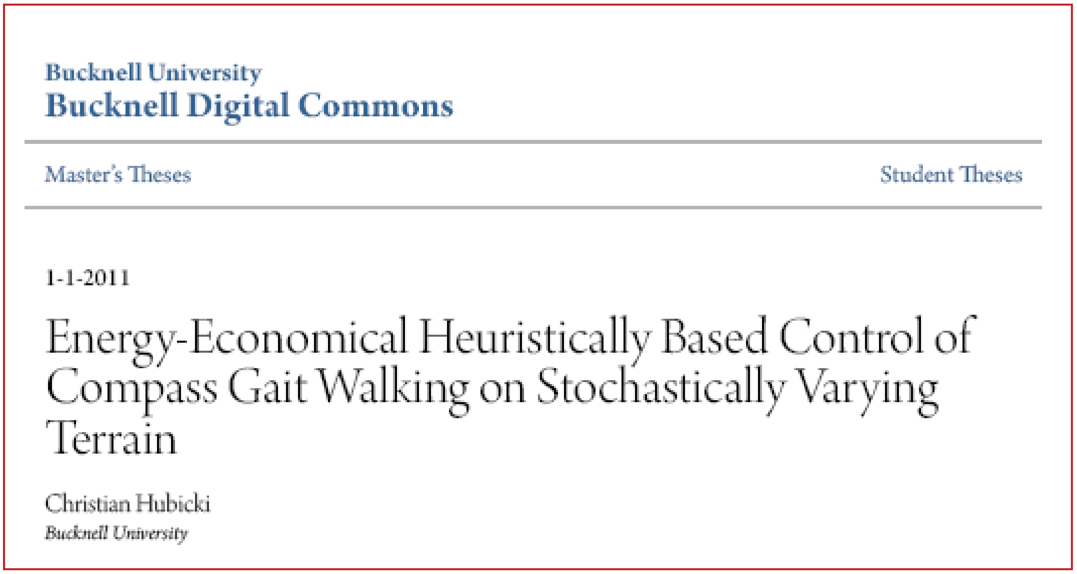

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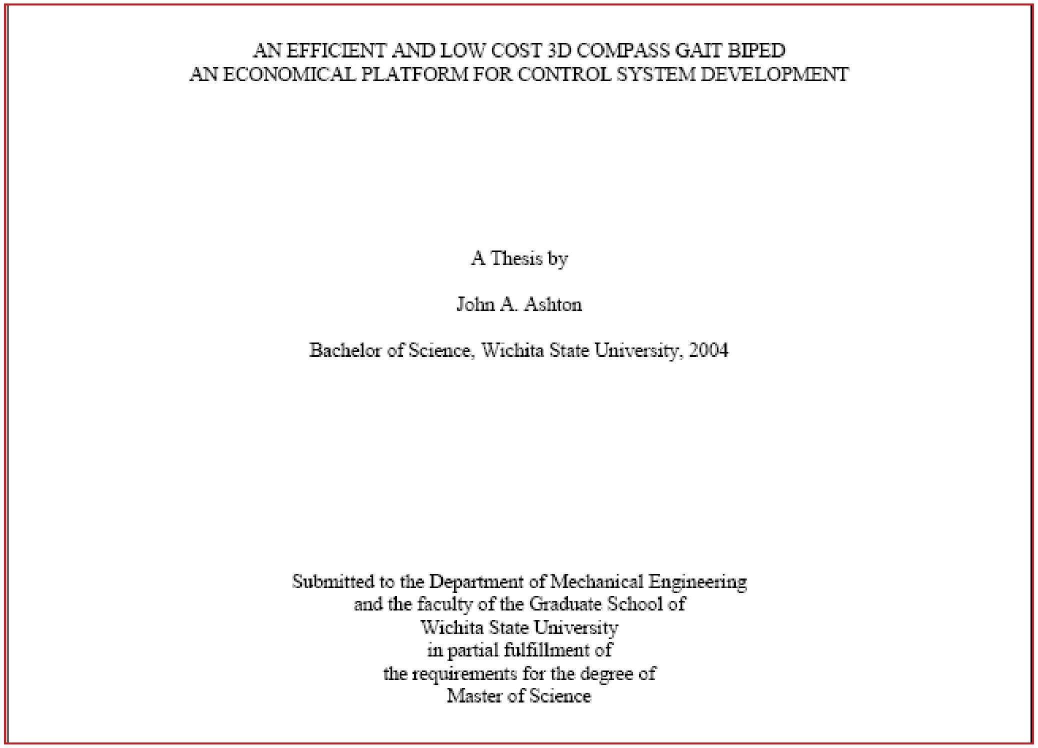
Energy-Economical Heuristically Based Control of Compass Gait Walking on Stochastically Varying Terrain

Christian Hubicki
Bucknell University



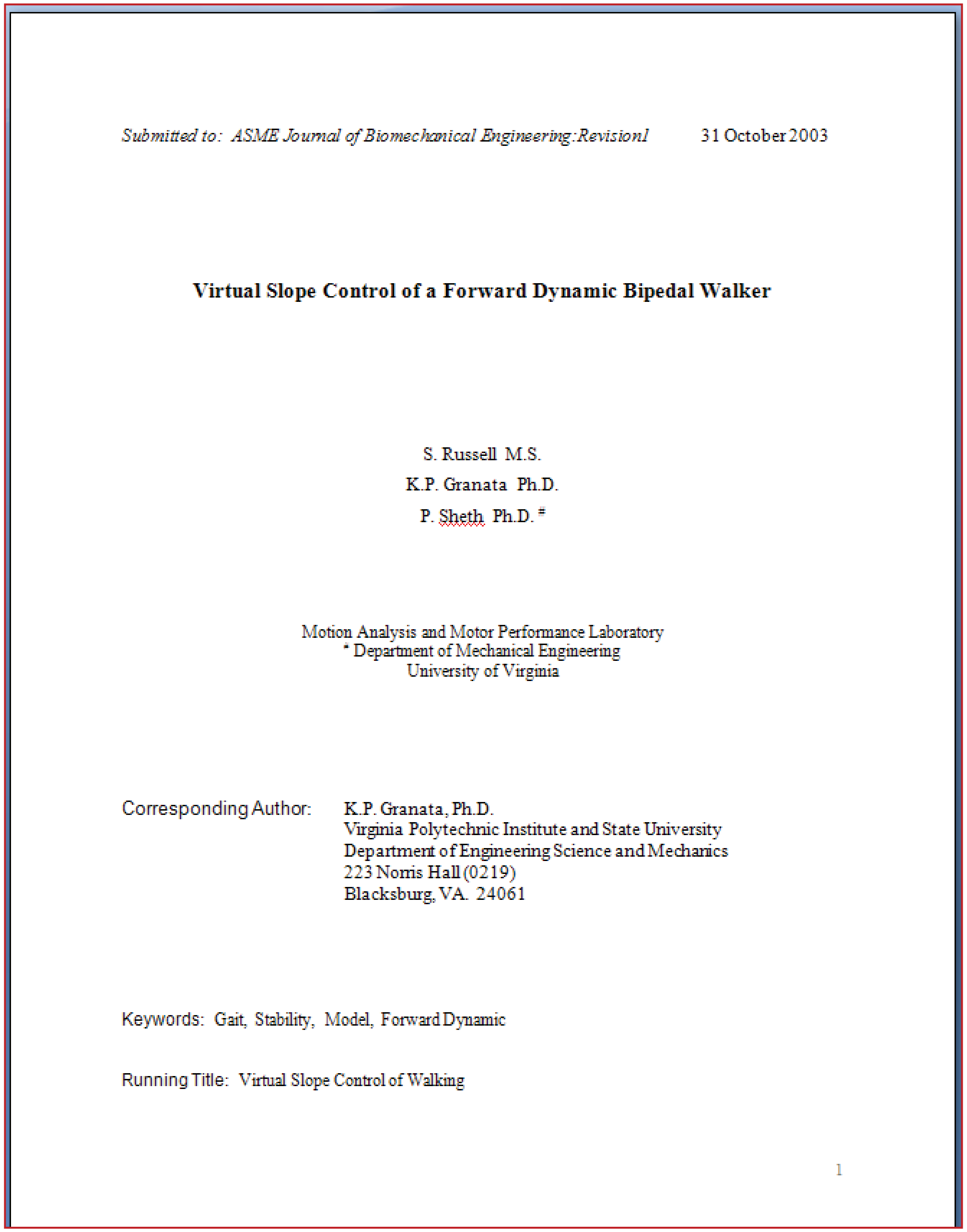
AN EFFICIENT AND LOW COST 3D COMPASS GAIT BIPED
AN ECONOMICAL PLATFORM FOR CONTROL SYSTEM DEVELOPMENT

A Thesis by

John A. Ashton

Bachelor of Science, Wichita State University, 2004

Submitted to the Department of Mechanical Engineering
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science



Submitted to: ASME Journal of Biomechanical Engineering:Revision1 31 October 2003

Virtual Slope Control of a Forward Dynamic Bipedal Walker

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Keywords: Gait, Stability, Model, Forward Dynamic

Running Title: Virtual Slope Control of Walking

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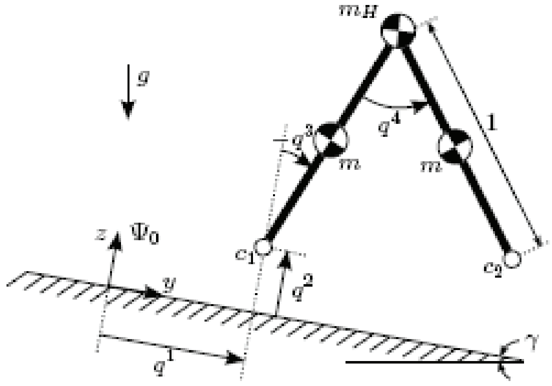

Figure 4.2: Setup and choice of coordinates and parameters for a planar straight-legged walking mechanism on an inclined flat floor.

exist. Furthermore, the optimization problem (4.1) can be extended, for example to include extra adjustable passive elements, which is exploited in Chapter 5.

The resulting gaits, obtained from either the Poincaré method or the optimization procedure, are periodic solutions to the dynamics equations. Whether these solution are stable or not, and how large the region of attraction of stable solutions is, is not determined by either gait search method. Especially for pure passive dynamic walking (in which case no control is available to stabilize the system), the region of attraction is very important: it determines whether a setup will actually be able to walk in practice, under the influence of disturbances and modeling errors.

4.2 A planar compass-gait walker

As a first example of the modeling and analysis techniques for walking robots, we consider the planar mechanism shown schematically in Figure 4.2. It consists of two legs with a point mass m at their centers, joined by a hip joint of mass m_H. The feet c_1 and c_2 can come in contact with the ground, which is tilted at an angle γ as shown in the figure. This robot is often called the compass-gait walker, because its mechanical structure is like that of a compass used for drawing circles.

The compass-gait walker has been studied by many different people in literature, mainly because it is the simplest possible mechanism that can still exhibit walking behavior. Its continuous dynamic equations are simple enough to be managed by hand, yet the total dynamics including impacts and contact switching possesses very interesting behavior involving stable passive limit cycles and bifurcations (see Goswami et al. (1998) for a presentation of these aspects). In this

---

Design, Construction, and Experiments with a Compass Gait Walking Robot

by

Zachary J Jackowski

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2011

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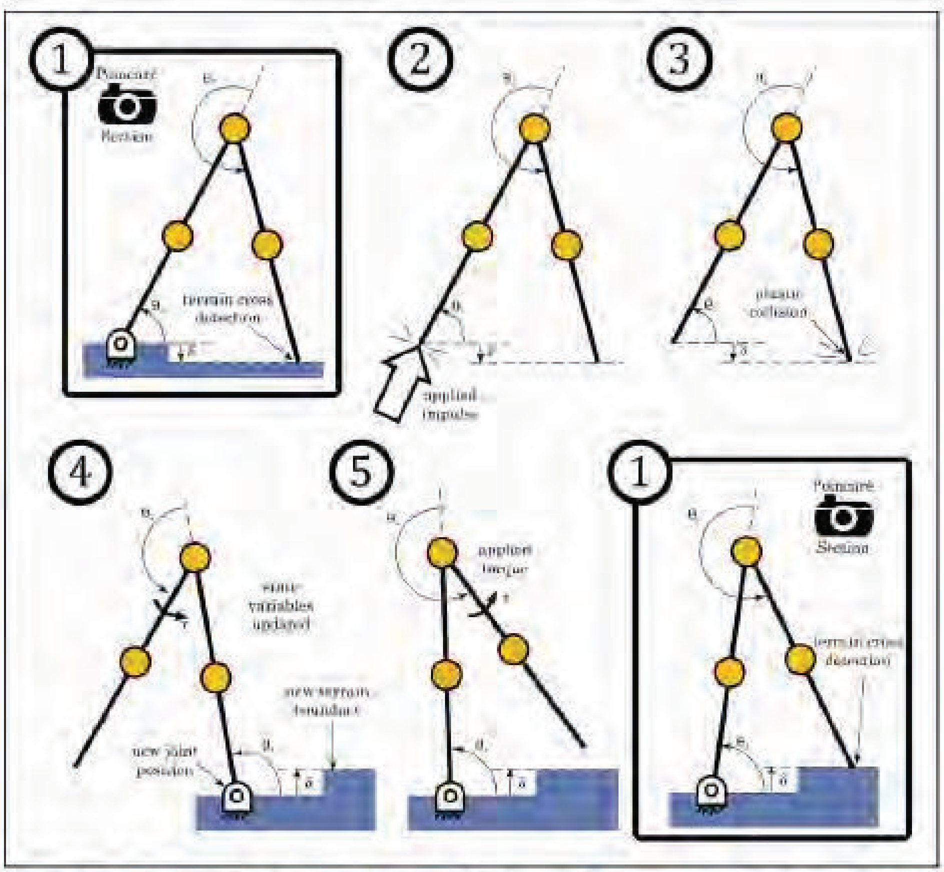


Figure 2.1: Five stages of the single-step transfer function beginning at Poincare section i and terminating at section $i+1$: detect terrain crossing of lead leg, apply instantaneous impulse in line with trailing leg, compute plastic collision at leading leg, swap ground revolute joint and state variables, compute continuous dynamics with hip-torque actuation until terrain cross is detected

Chapter 5

The Compass Gait Biped

In this chapter we apply the extended control law from the previous chapter to a special class of biped robots.

We will sometimes use the following shorthand notation; g.s for ground slop, i.c for integral curve, sec for seconds, rad for radians, deg for degrees, m for meters (or mass) and Kg for kilograms.

This chapter is based on [SB02], [GEK97] and [GTE98].

5.1 The Model

We consider a very simple model of a biped robot, the compass gait biped (CGB) shown in figure 5.1.

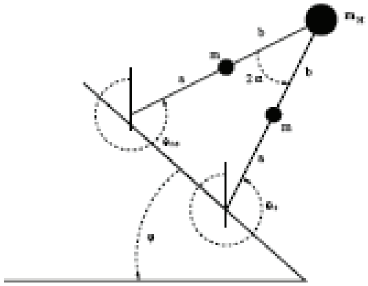


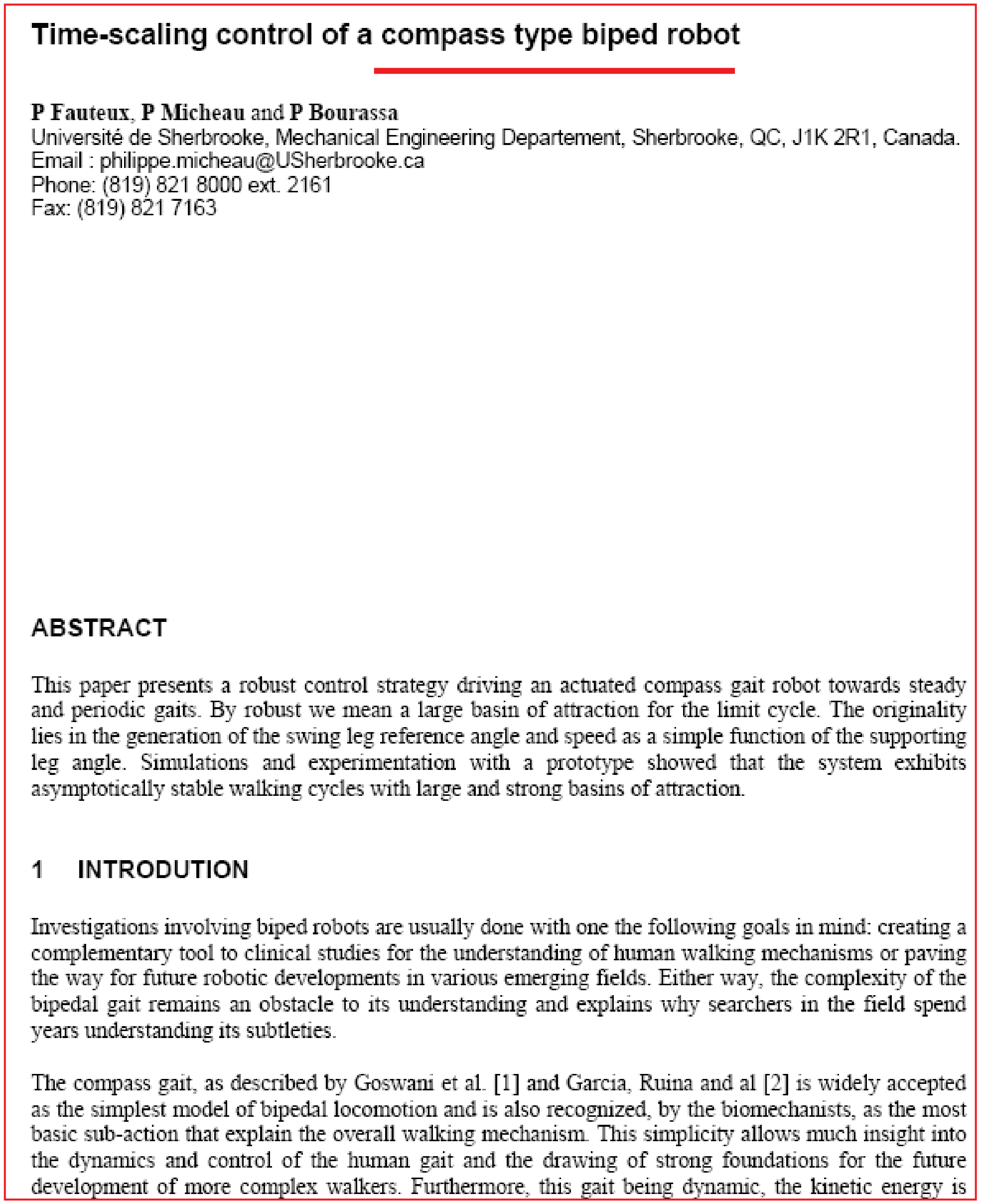
Figure 5.1: The Compass Gait Biped (CGB).

The details of the model are as follows:

i The mass is concentrated at 3 points; mass m_H at the hip and masses m on each leg, located at distances a and b from the leg tip and the hip, respectively. During simulation m_H=10Kg and m=5Kg.

ii The legs are identical and during simulation $a = b = 0,5m$.

Papers that have been published following our work…



Time-scaling control of a compass type biped robot

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ABSTRACT

This paper presents a robust control strategy driving an actuated compass gait robot towards steady and periodic gaits. By robust we mean a large basin of attraction for the limit cycle. The originality lies in the generation of the swing leg reference angle and speed as a simple function of the supporting leg angle. Simulations and experimentation with a prototype showed that the system exhibits asymptotically stable walking cycles with large and strong basins of attraction.

1 INTRODUTION

Investigations involving biped robots are usually done with one the following goals in mind: creating a complementary tool to clinical studies for the understanding of human walking mechanisms or paving the way for future robotic developments in various emerging fields. Either way, the complexity of the bipedal gait remains an obstacle to its understanding and explains why searchers in the field spend years understanding its subtleties.

The compass gait, as described by Goswani et al. [1] and Garcia, Ruina and al [2] is widely accepted as the simplest model of bipedal locomotion and is also recognized, by the biomechanists, as the most basic sub-action that explain the overall walking mechanism. This simplicity allows much insight into the dynamics and control of the human gait and the drawing of strong foundations for the future development of more complex walkers. Furthermore, this gait being dynamic, the kinetic energy is

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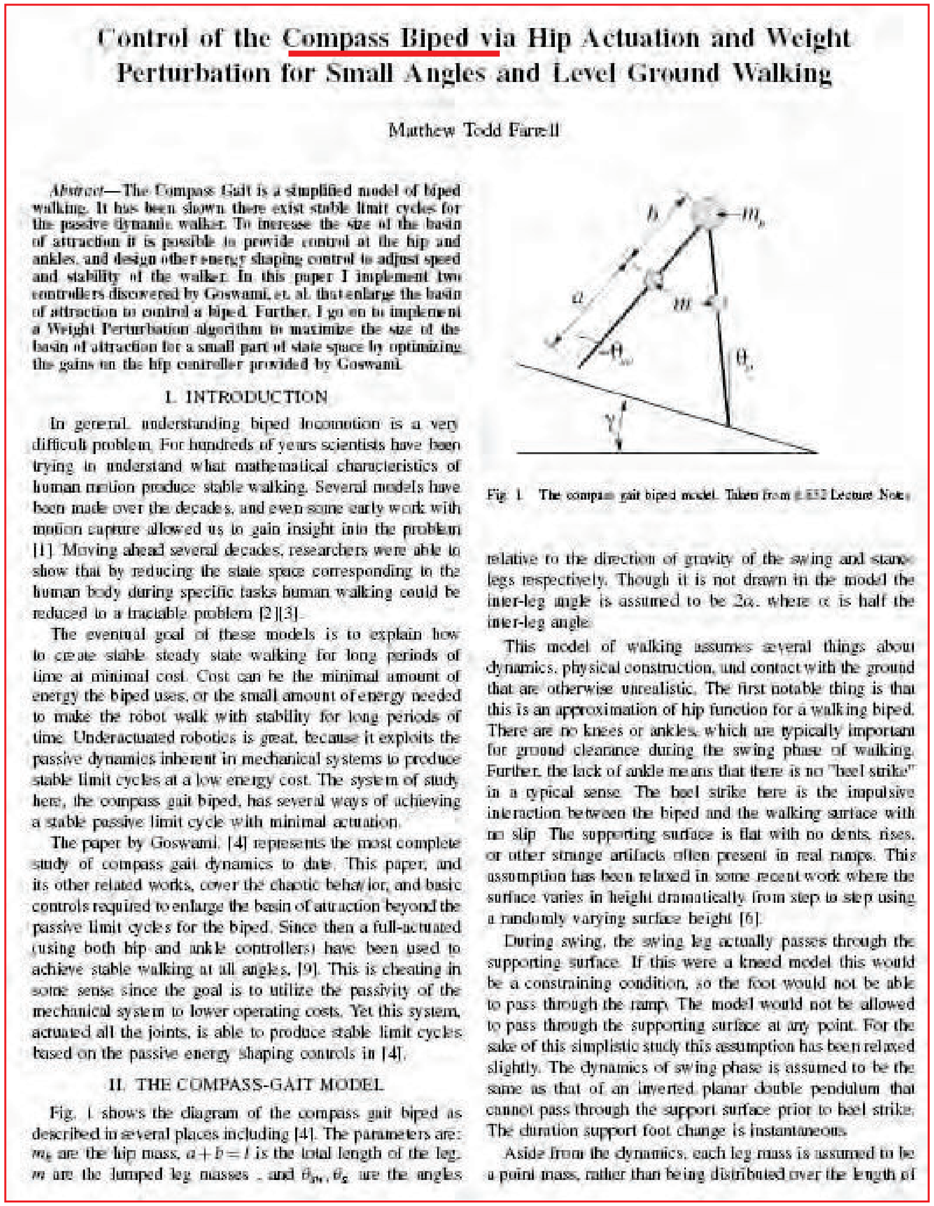


Control of the Compass Biped via Hip Actuation and Weight Perturbation for Small Angles and Level Ground Walking

Matthew Todd Farrell

Abstract—The Compass Gait is a simplified model of biped walking. It has been shown there exist stable limit cycles for the passive dynamic walker. To increase the size of the basin of attraction it is possible to provide control at the hip and ankles, and design other energy shaping control to adjust speed and stability of the walker. In this paper I implement two controllers discovered by Goswami, et. al. that enlarge the basin of attraction to control a biped. Further, I go on to implement a Weight Perturbation algorithm to maximize the size of the basin of attraction for a small part of state space by optimizing the gains on the hip controller provided by Goswami.

I. INTRODUCTION

In general, understanding biped locomotion is a very difficult problem. For hundreds of years scientists have been trying to understand what mathematical characteristics of human motion produce stable walking. Several models have been made over the decades, and even some early work with motion capture allowed us to gain insight into the problem [1]. Moving ahead several decades, researchers were able to show that by reducing the state space corresponding to the human body during specific tasks human walking could be reduced to a tractable problem [2][3].

The eventual goal of these models is to explain how to create stable steady state walking for long periods of time at minimal cost. Cost can be the minimal amount of energy the biped uses, or the small amount of energy needed to make the robot walk with stability for long periods of time. Underactuated robotics is great, because it exploits the passive dynamics inherent in mechanical systems to produce stable limit cycles at a low energy cost. The system of study here, the compass gait biped, has several ways of achieving a stable passive limit cycle with minimal actuation.

The paper by Goswami, [4] represents the most complete study of compass gait dynamics to date. This paper, and its other related works, cover the chaotic behavior, and basic controls required to enlarge the basin of attraction beyond the passive limit cycles for the biped. Since then a full-actuated (using both hip and ankle controllers) have been used to achieve stable walking at all angles, [9]. This is cheating in some sense since the goal is to utilize the passivity of the mechanical system to lower operating costs. Yet this system, actuated all the joints, is able to produce stable limit cycles based on the passive energy shaping controls in [4].

II. THE COMPASS-GAIT MODEL

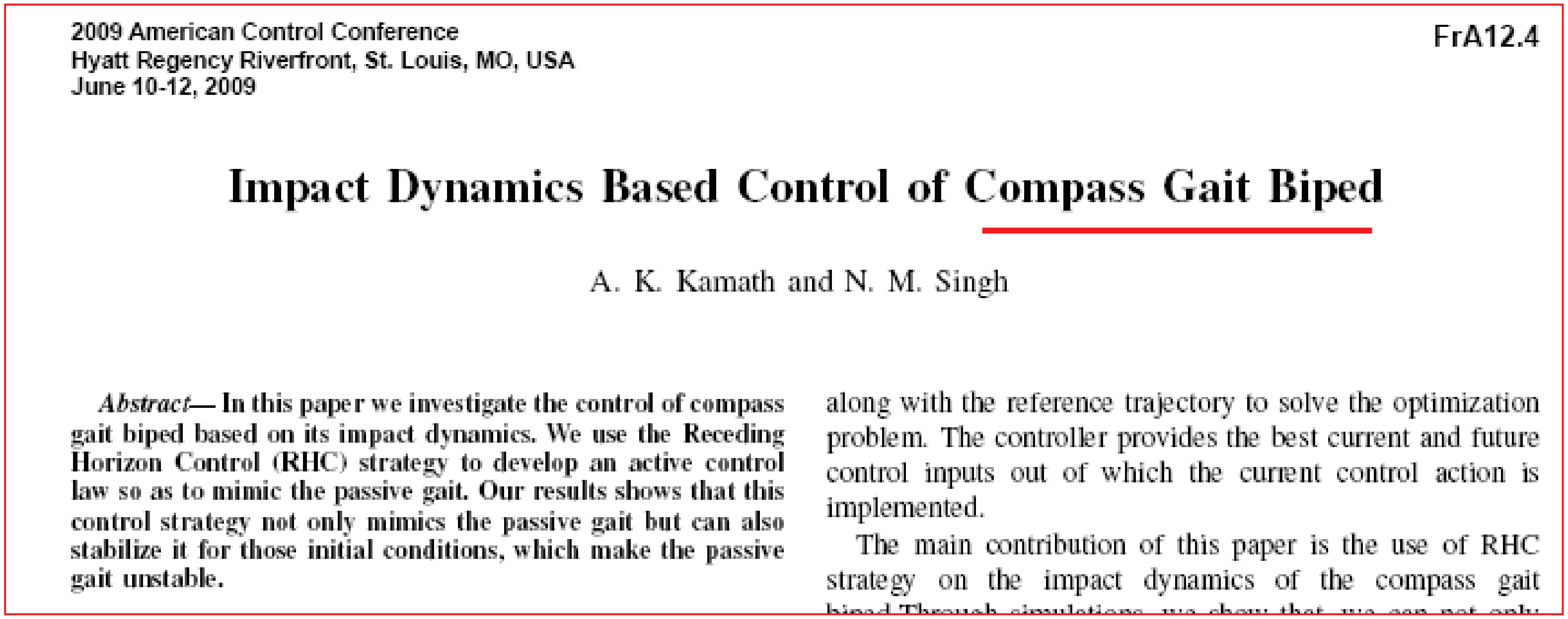
Fig. 1 shows the diagram of the compass gait biped as described in several places including [4]. The parameters are: m_h are the hip mass, $a+b=l$ is the total length of the leg. m are the lumped leg masses . and θ_{sw}, θ_s are the angles relative to the direction of gravity of the swing and stance legs respectively. Though it is not drawn in the model the inter-leg angle is assumed to be 2α, where α is half the inter-leg angle.

Fig. 1. The compass gait biped model. Taken from 6.832 Lecture Notes

This model of walking assumes several things about dynamics, physical construction, and contact with the ground that are otherwise unrealistic. The first notable thing is that this is an approximation of hip function for a walking biped. There are no knees or ankles, which are typically important for ground clearance during the swing phase of walking. Further, the lack of ankle means that there is no "heel strike" in a typical sense. The heel strike here is the impulsive interaction between the biped and the walking surface with no slip. The supporting surface is flat with no dents, rises, or other strange artifacts often present in real ramps. This assumption has been relaxed in some recent work where the surface varies in height dramatically from step to step using a randomly varying surface height [6].

During swing, the swing leg actually passes through the supporting surface. If this were a kneed model this would be a constraining condition, so the foot would not be able to pass through the ramp. The model would not be allowed to pass through the supporting surface at any point. For the sake of this simplistic study this assumption has been relaxed slightly. The dynamics of swing phase is assumed to be the same as that of an inverted planar double pendulum that cannot pass through the support surface prior to heel strike. The duration support foot change is instantaneous.

Aside from the dynamics, each leg mass is assumed to be a point mass, rather than being distributed over the length of



2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

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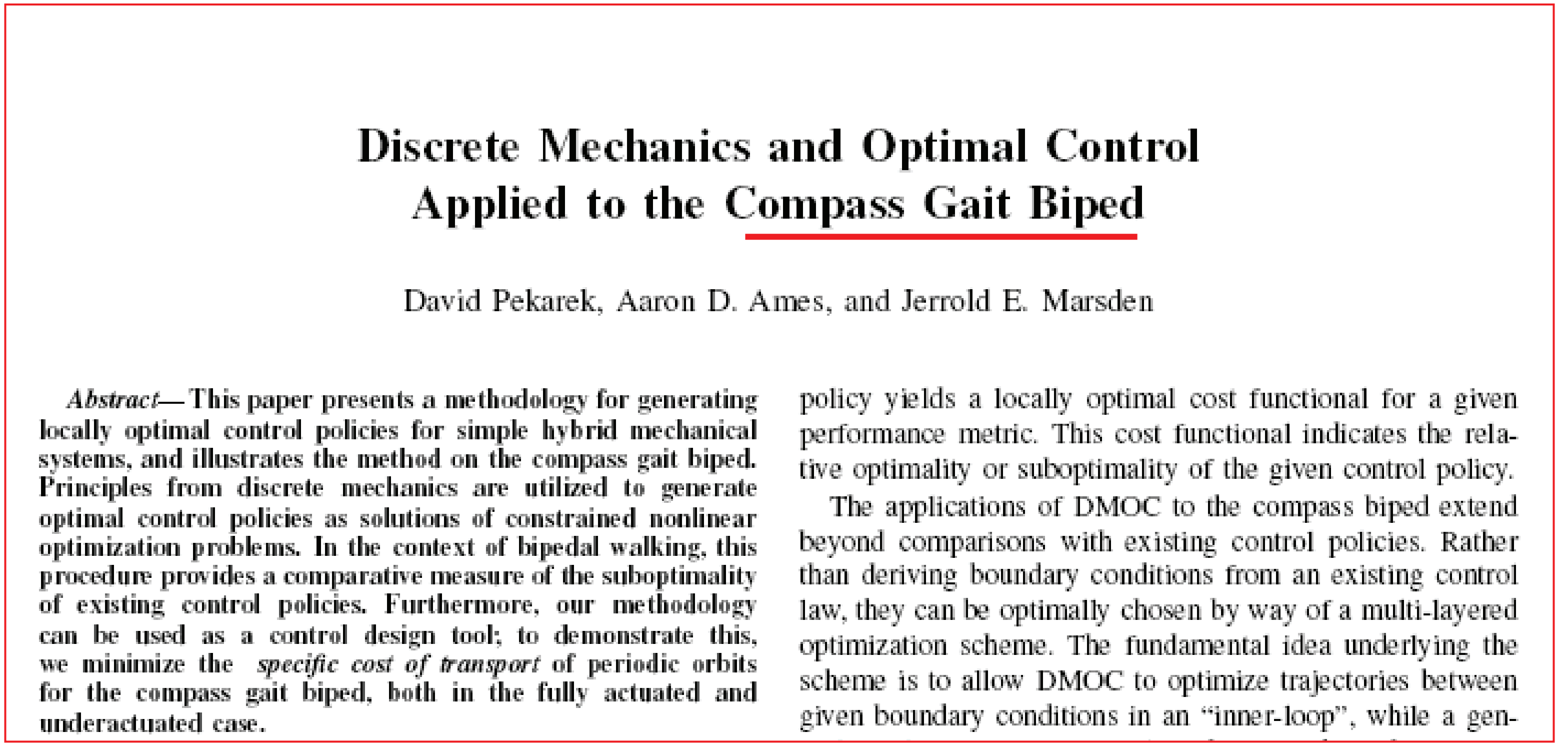
Impact Dynamics Based Control of Compass Gait Biped

A. K. Kamath and N. M. Singh

***Abstract*— In this paper we investigate the control of compass gait biped based on its impact dynamics. We use the Receding Horizon Control (RHC) strategy to develop an active control law so as to mimic the passive gait. Our results shows that this control strategy not only mimics the passive gait but can also stabilize it for those initial conditions, which make the passive gait unstable.**

along with the reference trajectory to solve the optimization problem. The controller provides the best current and future control inputs out of which the current control action is implemented.

The main contribution of this paper is the use of RHC strategy on the impact dynamics of the compass gait biped Through simulations, we show that we can not only



Discrete Mechanics and Optimal Control Applied to the Compass Gait Biped

David Pekarek, Aaron D. Ames, and Jerrold E. Marsden

***Abstract*—This paper presents a methodology for generating locally optimal control policies for simple hybrid mechanical systems, and illustrates the method on the compass gait biped. Principles from discrete mechanics are utilized to generate optimal control policies as solutions of constrained nonlinear optimization problems. In the context of bipedal walking, this procedure provides a comparative measure of the suboptimality of existing control policies. Furthermore, our methodology can be used as a control design tool; to demonstrate this, we minimize the *specific cost of transport* of periodic orbits for the compass gait biped, both in the fully actuated and underactuated case.**

policy yields a locally optimal cost functional for a given performance metric. This cost functional indicates the relative optimality or suboptimality of the given control policy.

The applications of DMOC to the compass biped extend beyond comparisons with existing control policies. Rather than deriving boundary conditions from an existing control law, they can be optimally chosen by way of a multi-layered optimization scheme. The fundamental idea underlying the scheme is to allow DMOC to optimize trajectories between given boundary conditions in an "inner-loop", while a gen-

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Reduction-based Control of Three-dimensional Bipedal Walking Robots

Abstract

In this paper we develop the concept of reduction-based control, which is founded on a controlled form of geometric reduction known as functional Routhian reduction. We prove a geometric property of general serial-chain robots termed recursive cyclicity, identifying the inherent robot symmetries that we exploit with the Subrobot Theorem. This shows that any serial-chain robot can be decomposed for arbitrarily lower-dimensional analysis and control. We apply this method to construct stable directional three-dimensional walking gaits for a four-degree-of-freedom hipped bipedal robot. The controlled reduction decouples the biped's sagittal-plane motion from the yaw and lean modes, and on the sagittal subsystem we use passivity-based control to produce known planar limit cycles on flat ground. The unstable yaw and lean modes are separately controlled to 2-periodic orbits through their shaped momenta. We numerically verify the existence of stable 2-periodic straight-walking limit cycles and demonstrate turning capabilities for the controlled biped.

KEY WORDS—nonlinear control, symmetry, geometric reduction, generalized momentum, bipedal locomotion, passive dynamics, hybrid systems, limit cycle

1. Introduction

The implications of understanding bipedal locomotion are great owing to its human application. The potential for improving prosthetic limbs, navigating uneven terrestrial surfaces, and creating efficient locomotive mechanisms are among the many incentives that drive research in this field of robotics. The humanoid form of locomotion known as dynamic bipedal walking is based on "controlled falling", where each leg's step cycle involves a fall towards the ground until foot impact transfers this falling motion to the other leg (enabling a hybrid sense of stability for the walking gait). This is quite different from the "quasi-static" locomotion of the popular Honda Asimo and Sony Qrio robots. These bipeds maintain a static sense of stability during each step cycle, resulting in unnatural and inefficient shuffling motion (Kuo 2007).

The first significant studies in dynamic bipedal walking concerned simple models constrained to the sagittal plane (two-dimensional space), such as the uncontrolled two-link "compass-gait" biped of Figure 1, to roughly approximate human dynamic motion. McGeer (1990) discovered the existence of stable "passive" limit cycles down shallow slopes for the compass-gait biped, and passive dynamic walking was further studied by Goswami et al. (1996). Chevallereau et al. (2003) proved that stable limit cycles could be generated for underactuated planar walkers using a control method known as hybrid zero dynamics (Westervelt et al. 2003; Morris and Grizzle 2006), in which output linearization is employed to zero hybrid-invariant output functions (i.e. virtual constraints) describing the walking gait. These walking gaits were demonstrated on the planar RABBIT bipedal robot at the Laboratoire Automatique de Grenoble in France.

Although these concepts have been quite successful with regard to planar walking mechanisms, there has been scattered

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Preliminary results of this paper were present in Gregg and Spong, 2008. For simulation movies and additional model detail, visit http://decision.csl.uiuc.edu/~rgregg

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Compass gait mechanics account for top walking speeds in ducks and humans

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SUMMARY

The constraints to maximum walking speed and the underlying cause of the walk–run transition remains controversial. However, the motions of the body and legs can be reduced to a few mechanical principles, which, if valid, impose simple physics-based limits to walking speed. Bipedal walking may be viewed as a vaulting gait, with the centre of mass (CoM) passing over a stiff stance leg (an 'inverted pendulum'), while the swing leg swings forward (as a pendulum). At its simplest, this forms a 'compass gait' walker, which has a maximum walking speed constrained by simple mechanics: walk too fast, or with too high a step length, and gravity fails to keep the stance foot attached to the floor. But how useful is such an extremely reductionist model? In the present study, we report measurements on a range of duck breeds as example unspecialized, non-planar, crouch-limbed walkers and contrast these findings with previous measurements on humans, using the theoretical framework of compass gait walking. Ducks walked as inverted pendulums with near-passive swing legs up to relative velocities around 0.5, remarkably consistent with the theoretical model. By contrast, top walking speeds in humans cannot be achieved with passive swing legs: humans, while still constrained by compass gait mechanics, extend their envelope of walking speeds by using relatively high step frequencies. Therefore, the capacity to drive the swing leg forward by walking humans may be a specialization for walking, allowing near-passive vaulting of the CoM at walking speeds 4/3 that possible with a passive (duck-like) swing leg.

Supplementary material available online at http://jeb.biologists.org/cgi/content/full/211/23/3744/DC1

Key words: walk, run, gait, transition, inverted pendulum.

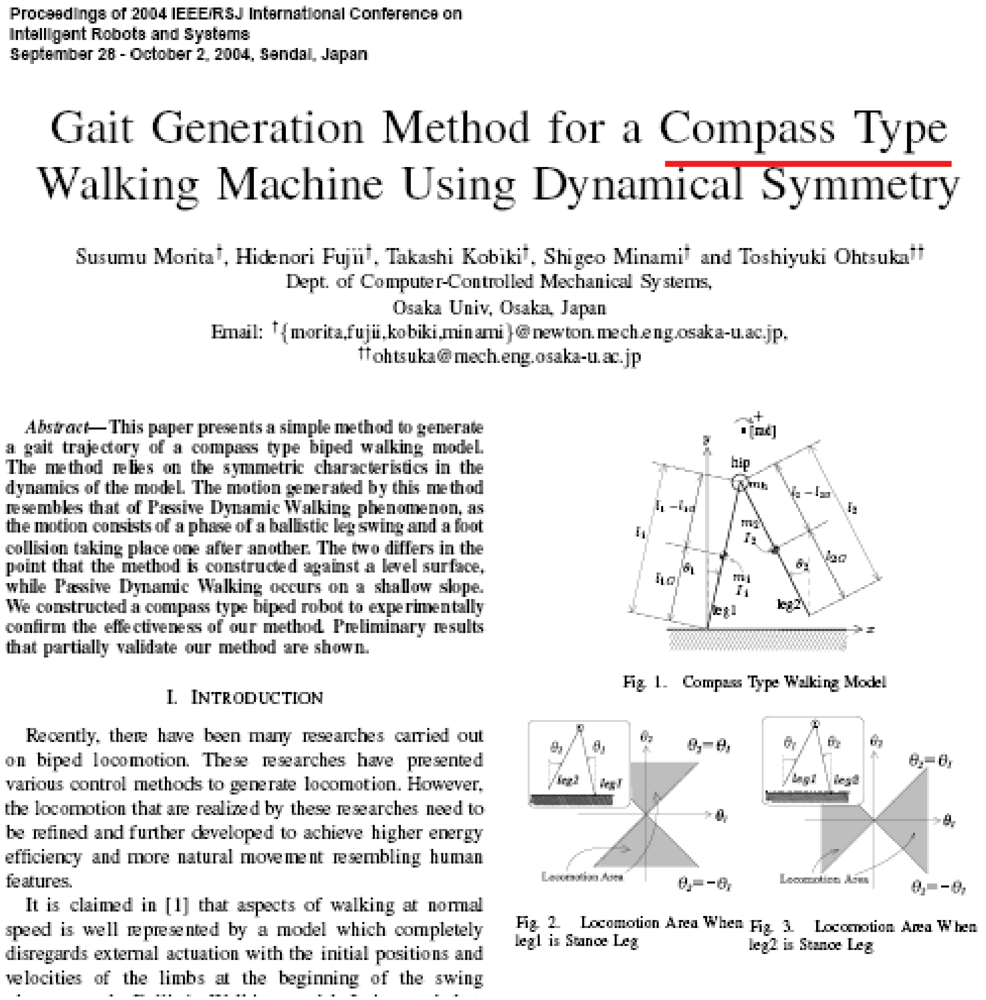
INTRODUCTION

Walking animals use immensely complex combinations of muscle and nerve actions to drive and control their limbs. However, the mechanical principles underlying walking may be simple and general. Walking – in humans at least – is a relatively stiff-limbed gait without aerial phases and is often described as acting as an 'inverted pendulum', with kinetic energy E_k at the beginning of each stance phase translating to gravitational potential energy E_p as the centre of mass (CoM) rises to its highest point near mid-stance, and returning as E_k as the body falls towards the end of stance. In its simplest form, walking as an inverted pendulum can be described by a 'compass gait' model (McGeer, 1990; Alexander, 1995; Goswami et al., 1997; Garcia et al., 1998) (see also Saunders et al., 1953; Kuo, 2007). This model is planar, has completely rigid limbs, exactly one point-foot in contact with the ground at any time and instantaneous transition

fascinating comparison with humans: is the mechanical approximation of a compass gait relevant to walking in such a non-specialized walker?

In the present study, we report forceplate-derived measurements of waddling, walking and running in three breeds of duck. We use the term 'energy recovery' (*ER*) (Cavagna et al., 1977) to describe the maximum potential for changes in CoM E_k and E_p to be passive, consistent with the inverted pendulum model of walking. We use *ER* to distinguish between 'walking' (high *ER*) and 'running' (low *ER*) gaits. The importance of lateral motions – 'waddling' – to the potential passive qualities of walking is demonstrated by calculating *ER*s both including and excluding the E_k associated with lateral motions.

The three duck breeds, Aylesbury, Mallard and Indian Runner, are all derived from mallards *Anas platyrhyncos* (Linnaeus 1758) but have radically different forms (Fig. 1A). The Aylesbury is large, selected



Proceedings of 2004 IEEE/RSJ International Conference on
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September 28 - October 2, 2004, Sendai, Japan

Gait Generation Method for a Compass Type Walking Machine Using Dynamical Symmetry

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Abstract—**This paper presents a simple method to generate a gait trajectory of a compass type biped walking model. The method relies on the symmetric characteristics in the dynamics of the model. The motion generated by this method resembles that of Passive Dynamic Walking phenomenon, as the motion consists of a phase of a ballistic leg swing and a foot collision taking place one after another. The two differs in the point that the method is constructed against a level surface, while Passive Dynamic Walking occurs on a shallow slope. We constructed a compass type biped robot to experimentally confirm the effectiveness of our method. Preliminary results that partially validate our method are shown.**

I. INTRODUCTION

Recently, there have been many researches carried out on biped locomotion. These researches have presented various control methods to generate locomotion. However, the locomotion that are realized by these researches need to be refined and further developed to achieve higher energy efficiency and more natural movement resembling human features.

It is claimed in [1] that aspects of walking at normal speed is well represented by a model which completely disregards external actuation with the initial positions and velocities of the limbs at the beginning of the swing

Fig. 1. Compass Type Walking Model

Fig. 2. Locomotion Area When leg1 is Stance Leg

Fig. 3. Locomotion Area When leg2 is Stance Leg

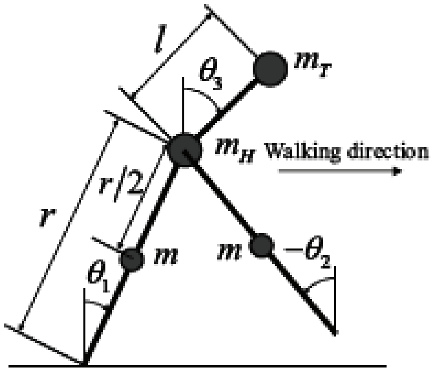

Figure 1. Biped knee-less walking robot

2. Biped walking model

2.1 Biped walking robot and model assumptions

The level-ground walking based on passive walk proposed in this paper needs a torso. In this paper, a simple biped robot with a torso shown in Fig. 1, is considered. This walking model is adding compass-like walking model (Goswami et al., 1996) to a torso, and has been studied in (Grizzle et al., 2001). The robot is composed of a torso, hips, and two legs. All

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The acrobot provides a particularly apt example for not c

systems, but also a simple model for walking machines called the

original compass gait walking model (Espiau 1994) as shown in Figu

acrobot, is a double pendulum actuated only through a torque appl

jointed hip. It is casually noted in recent papers (Byl 2008) that the

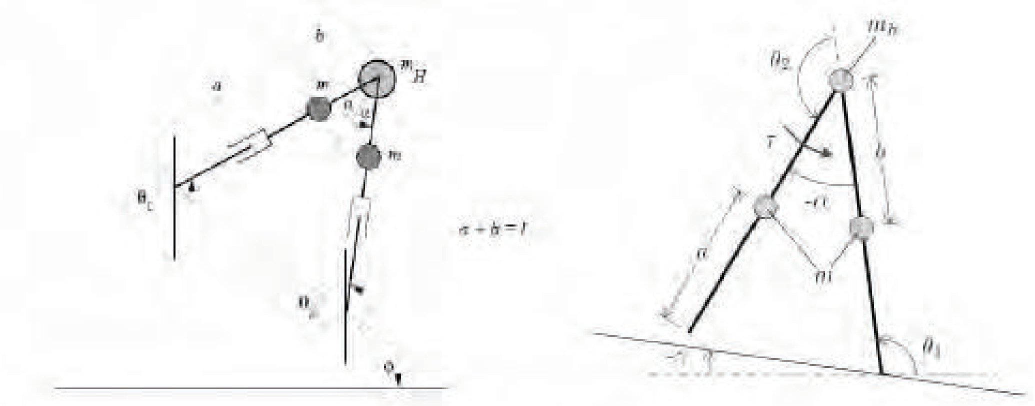
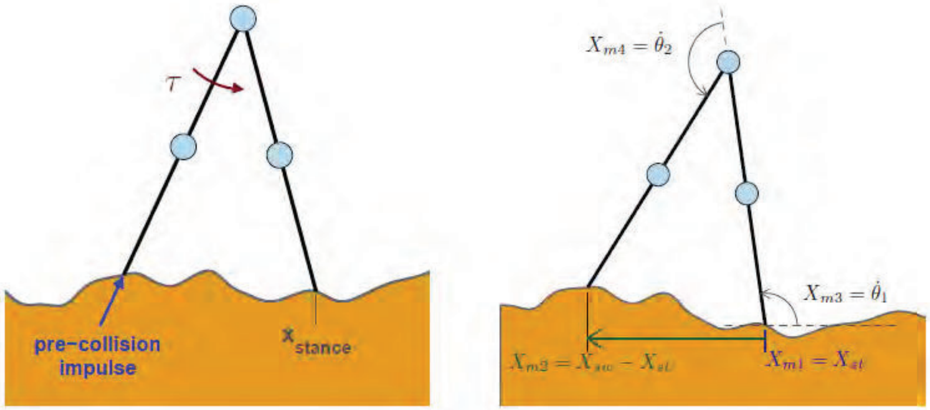
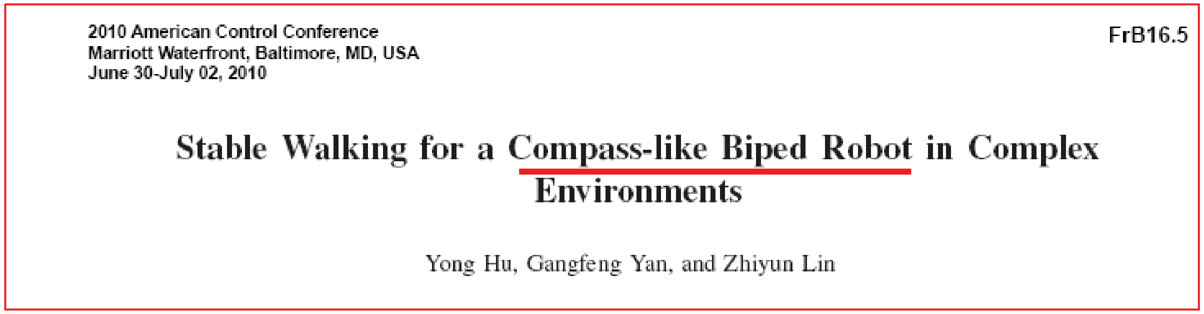


Figure 1.4: Visuals of the first reference (Espiau 1994) to the compass gait walking model (left) and its current implementation (Byl 2008) with a more obvious resembla to the Acrobot (right).





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Stable Walking for a Compass-like Biped Robot in Complex Environments

Yong Hu, Gangfeng Yan, and Zhiyun Lin

2.2 The Compass Gait Biped Robot (CGBR).

The compass gait biped robot was first introduced in [1]. It is a simplified versio of the PDW and similar to the one described in Figure 2 (see Figure 3), the main difference being that the masses are no longer constrained to being located only at the end of the leg (ie c no longer must be equal to 0). As with the PDW, the CGBR is assumed to always be in the swing phase except for when the support transfer phase occurs (remember this phase is considered to be instantaneous).

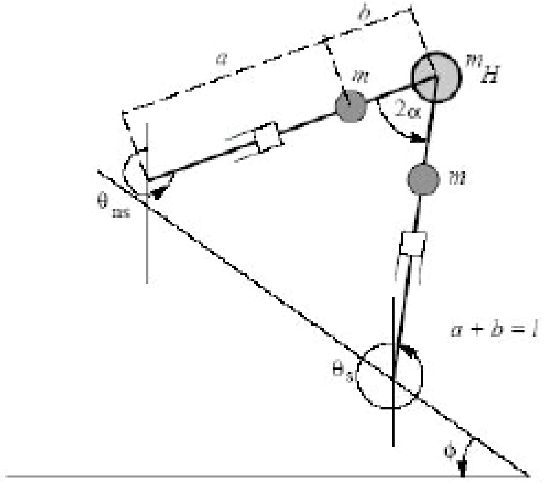
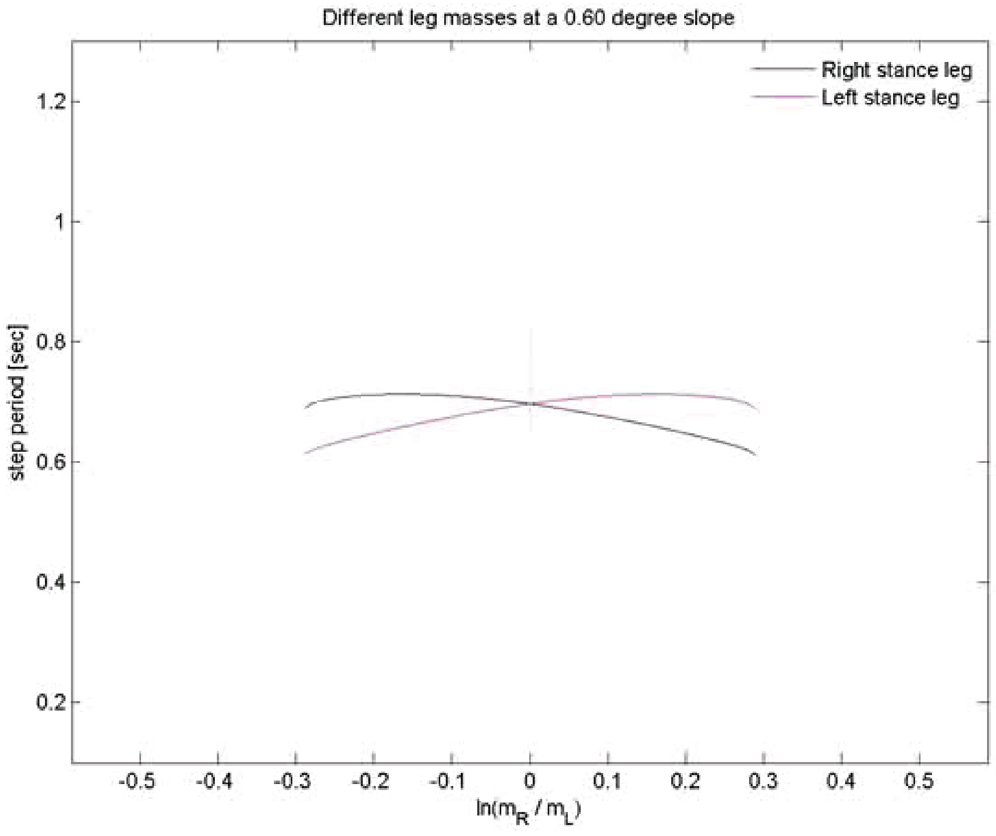


Figure 3 ~ The Compass Gait Biped Robot from [1]

The equation for the swing phase contains three major matrices: ***M*** the inertia matrix, ***N*** the centrifugal coefficients matrix and ***G*** the gravitational torque vector. The following is the equation:



Moon and Spong, 2010

Hardware building…

(most surprising for us)

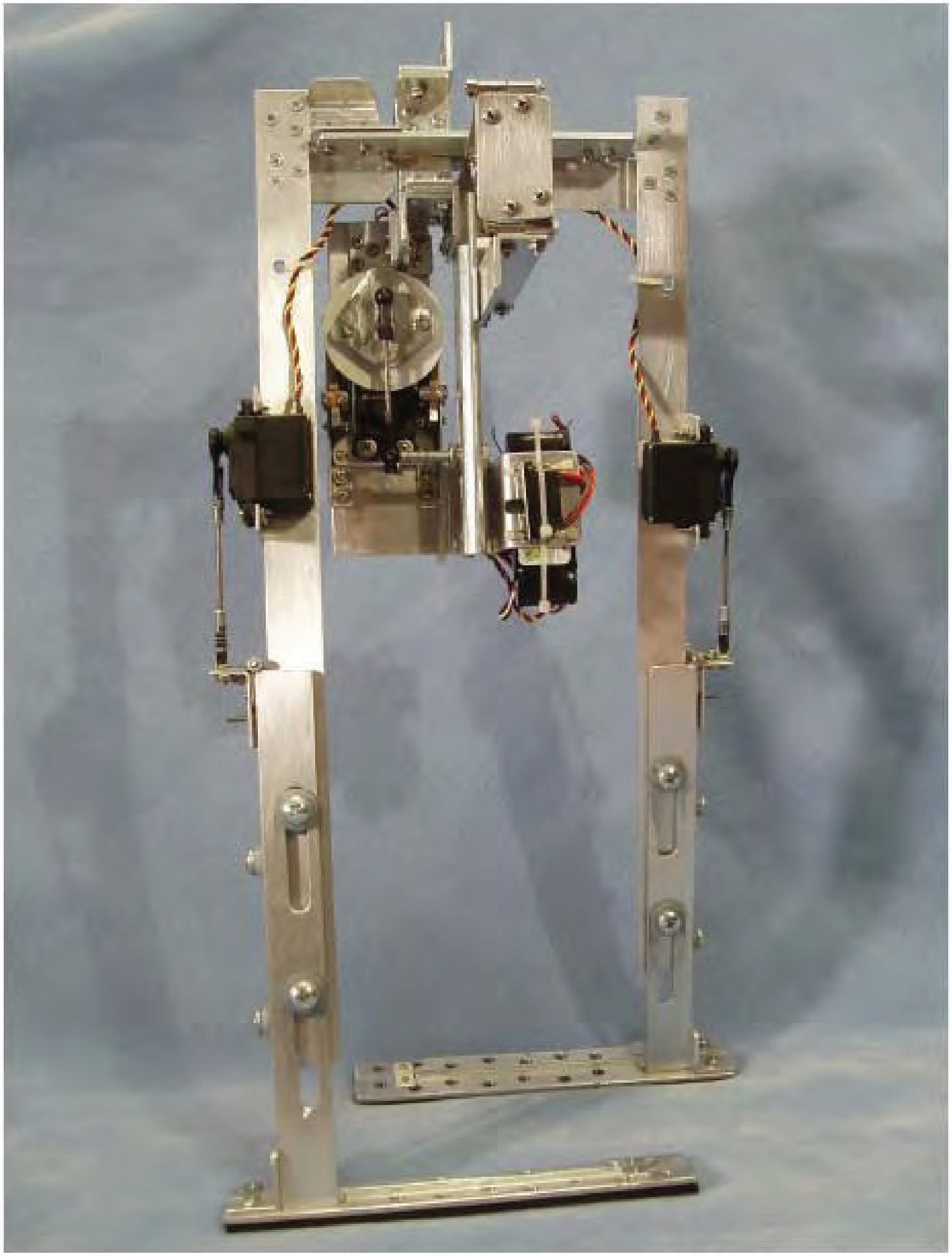


Figure 88. Full facial view of the completed AJP.

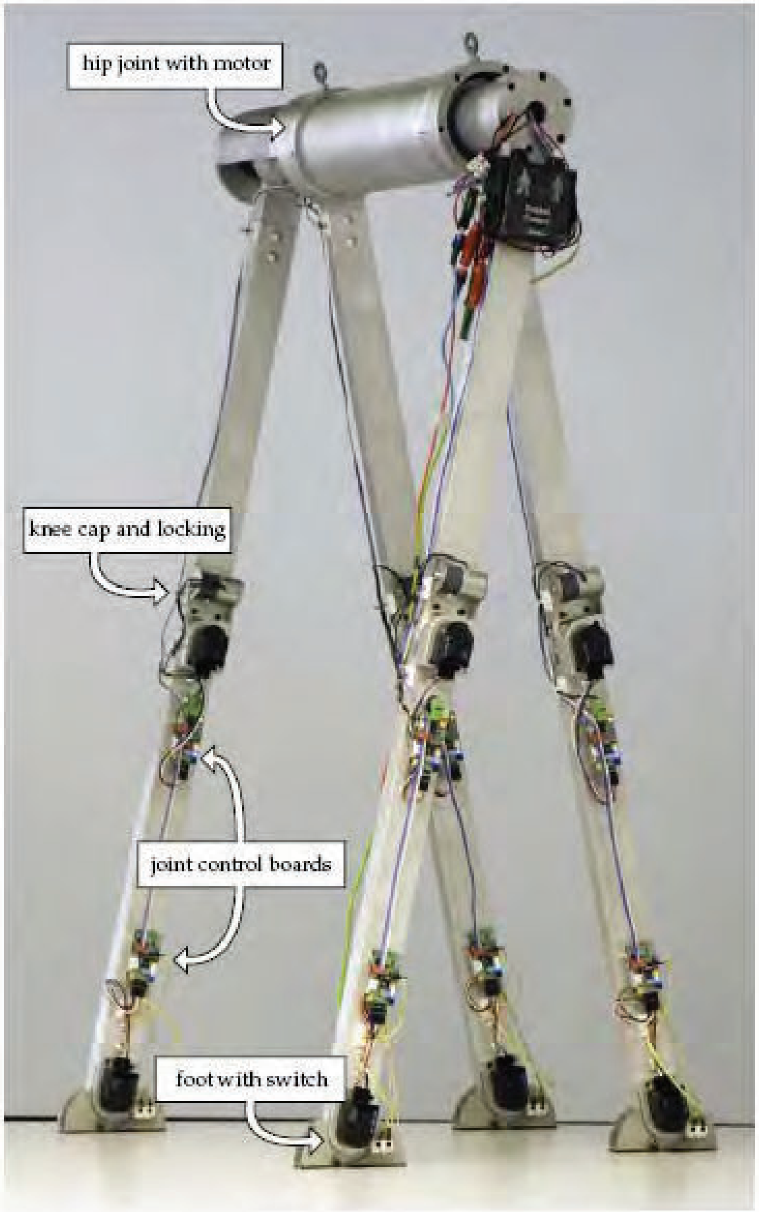


Figure 4.9: Experimental kneed walking robot 'Dribbel'.

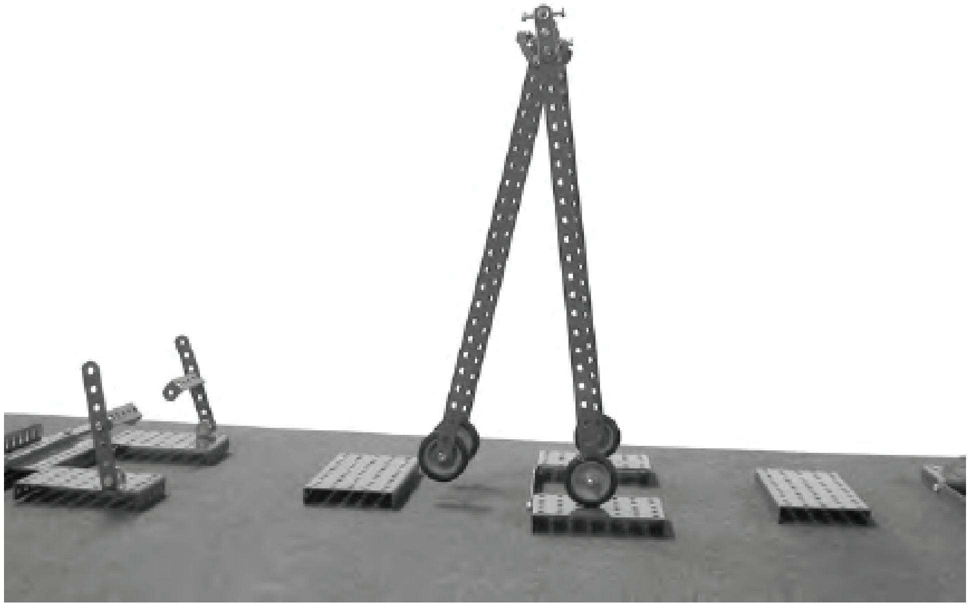


Figure 4.3: Experimental setup of a compass-gait walker that uses stepping stones to avoid toe stubbing of the swing leg.

Fig. 8 The experiment facilities

Figure 7-3: Compass gait robot posed on rough terrain.

Rigorous Stability Analysis

Model of Running

Raibert's Hopper (1984)

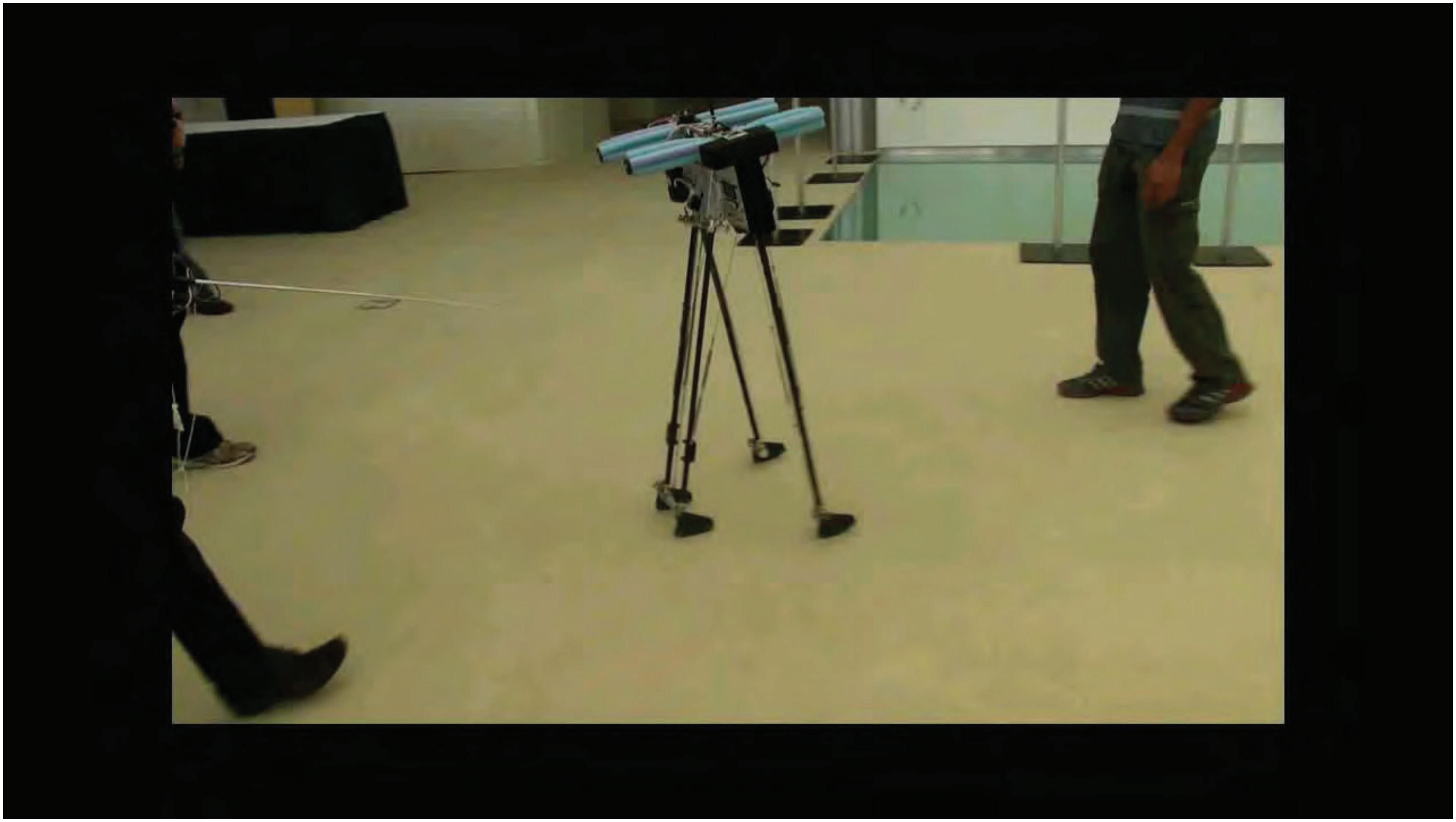
1991 Koditschek & Beuhler
1998 Francois & Samson

Model of Efficient Human Walking

Passive Walkers

(Collins, Wisse and Ruina, 2001)

McGeer 1990
Espiau & Goswani 1994
Ruina et al. 1997
Howell & Baillieul 1998
Kuo et al. 1999



Cornell Ranger, Dynamic Walking 2010

Capri or Naples, 1994

Poitiers, 1995

Strong in science.
Honest, fair, humble, friendly…

Collaborations:
Guy Bessonnet
Carlos Canudas de Wit
Bernard Brogliato
Philippe Sardain
Thierry Pozzo
Jean-Pierre Blanchi

Thanks!

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