Note of Fast Runner

Ken

June, 2018*

1 About systems and methods

1.1 Requirements - system

- List of assumptions
- Capture the required parameters (i.e. how to normalize the systems)
  - Resonance
  - Nonlinear elastic components
    - a set of linear components for multiple modes?
-

1.2 Requirements - method

- Applicable to complex system (e.g. for the designed mechanism)
- Nondimensionlization (so that it can be used for robots with different scales)
- Stability analysis
- Robustness

1.3 Remarks

- Impact does not cause velocity change on runner with massless leg!
- In SCS, to simulate massless leg, it is better to use only one body, and manipulate the relation between the contact point and the body in controller instead.

1.4 ToDo

- Rearrange/updating references for fastRunner
- Check if the foot is sliding
- Check optimization tools ihmc have
  - parameter optimization tool using Gradient Decent or GA
- Ask Cris about the parameter range/selection

*Last update: June 20, 2018

1.5 Questions

Direction

- Should I exclude the gyroscopic-based stabilization?
- Eigen values of linearized system, Poincare map analysis, anything else I should study for the stability analysis?
- The linkage between the control in simulation and mechanism design
  - Parameters
  - How to design a mechanism can emulate PD control?

General Utilities

- Any solver for nonlinear program IHMC used?
- Any trajectory optimization package IHMC used?
- Methods to get stable Reciprocating Spoked Runner?

  Past simulations

- Why the abstract runner (in spoked runner project) can be stabilized in x direction?

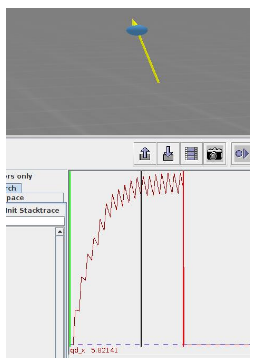

Figure 1: The Abstract Runner

  - The simulation setup is really robust for a large set of initial conditions/throttle angles
  - It turns out its because the added <u>wind resistance</u> dissipate a lot of energies.

- Methods to get stable Reciprocating Spoked Runner?
- What is the line <u>private static final long serialVersionUID</u> for?

2 Study

2.1 Jorge Cham's Dissertation - openloop control of 1DOF vertical hopper

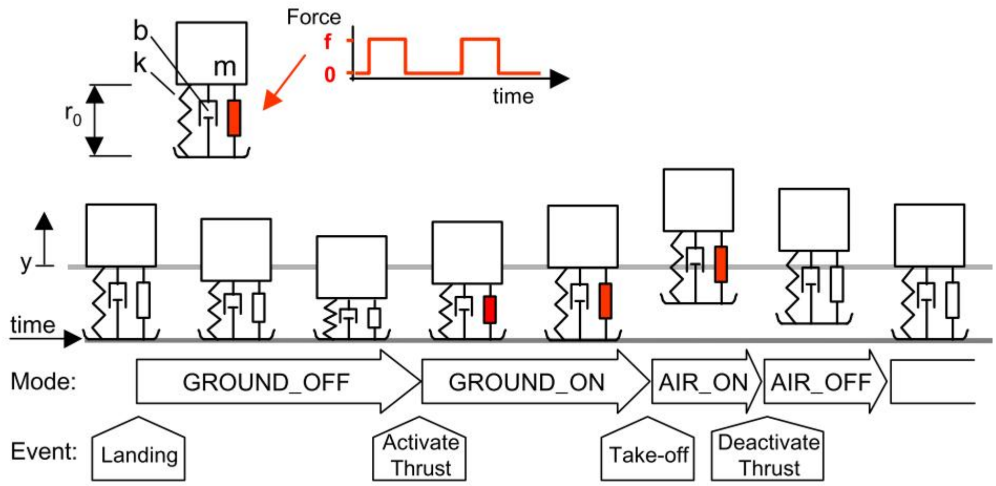

Figure 3-1. The vertical hopping model used for analysis. The hopper's leg consists of a spring, a damper and a force element which is active according to a binary motor pattern. The figure shows a sample trajectory of the hopper, the different modes that it goes through, and the events that trigger the transitions between the modes.

Figure 2: The schematic of a 1 DOF hopper [11]

2.1.1 System assumptions

- massless leg
- open-loop force control

2.1.2 Sequence

{AIR_OFF, GROUND_OFF, GROUND_ON, AIR_ON}

2.1.3 Equation of motion

Using the model as shown in Fig. 2, during the stand phase (i.e. $y \leq 0$), the equation of motion can be expressed as:

$$m\ddot{y} = -b\dot{y} + -ky - mg + f$$

where m is the mass, b is the damping, k is the stiffness, f is the control input. Normalized by weight, the equation becomes

$$\ddot{y} = -b/m\dot{y} + -k/my - g + f/m$$

Expressed in state space form:

$$\begin{bmatrix} \dot{y} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/m & -b/m \end{bmatrix} \begin{bmatrix} y \\ \dot{y} \end{bmatrix} + \begin{bmatrix} 0 \\ -g + f/m \end{bmatrix} \tag{1}$$

or equivalently

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ -\omega^2 & -2\xi\omega \end{bmatrix} X + \begin{bmatrix} 0 \\ -g + f_n(t) \end{bmatrix} = AX + B \tag{2}$$

where $X \triangleq [y, \dot{y}]^T$. When the hopper is in the air (i.e. $y > 0$, flight phase),

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} X + \begin{bmatrix} 0 \\ -g \end{bmatrix} \tag{3}$$

Define the force of an open-loop motor pattern

$$f_n(t) = \begin{cases} f/m, & \text{if } t_{off} < t < t_{off} + t_{on}. \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Solutions

For (3):

$$X(t) = \begin{bmatrix} 1 & t \\ 0 & 0 \end{bmatrix} X_0 + \begin{bmatrix} t^2/2 \\ t \end{bmatrix} (-g) \tag{5}$$

For (2) when actuator is on:

$$X(t) = e^{At}(X_0 - X_{eq_{on}}) + X_{eq_{on}} \tag{6}$$

For (2) when actuator is off:

$$X(t) = e^{At}(X_0 - X_{eq_{off}}) + X_{eq_{off}} \tag{7}$$

where $X_{eq_{on}}$ and $X_{eq_{off}}$ are the equilibrium states:

$$X_{eq_{on}} = [\frac{f_n - g}{\omega^2}, 0]^T \tag{8}$$

$$X_{eq_{off}} = [\frac{-g}{\omega^2}, 0]^T \tag{9}$$

2.1.4 Stability Analysis

Eigen values For (3), eigen values are ± 1, in inherently unstable. (Why this does not matter? Because the contact)
For (2), eigen values are $-\xi\omega \pm \omega\sqrt{(\xi^2 - 1)} = -\omega(\xi \pm \sqrt{\xi^2 - 1}) = -\omega(\xi \pm i\sqrt{1 - \xi^2})$ As long as $\omega$and $\xi$are larger than zero, the **unforced** system is stable.

Poincare Method: The rest part skipped
Reasons: For more complex systems, hard to analytically derive the Poincare map (usually no closed-form solution). Found a package in spokeRunner simulation for Poincare Analysis (numerically), plan to reuse it.

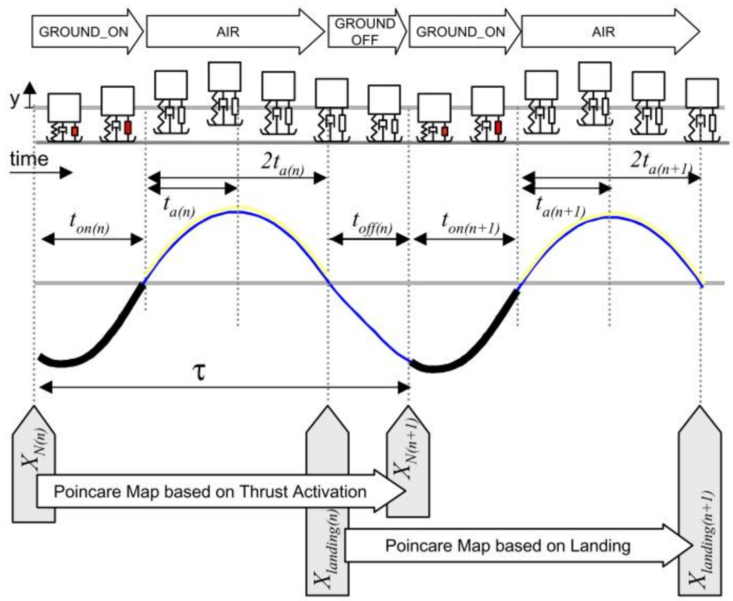

Figure 3-2. Illustration of a sample time history of the vertical hopper. The figure shows the two possibilities for formulating the Poincare Map used in analysis: a Map based on the state at thrust activation, and a Map based on the velocity and time at landing.

Figure 3: The modes of the hopper [11]

Assumptions:

- the period is T
- two modes need to be checked
- $X(0) = X_{N_n}$ where n indicates the n^{th} trajectory

Using Equations 6, we can derive

$$X(t_{on_n}) = e^{At_{on_n}}(X_{N_n} - X_{eq_{on}}) + X_{eq_{on}}$$

Use the fact that

$$X(t_{on_n} + 2t_{a_n}) = -X(t_{on_n})$$

Then we can calculate the $X_{N_{n+1}}$ as follows:

$$\begin{aligned} X_{N_{n+1}} &= e^{A(T-2t_{a_n}-t_{on_n})}(-X(t_{on_n}) - X_{eq_{off}}) + X_{eq_{off}} \\ X_{N_{n+1}} &= e^{A(T-2t_{a_n}-t_{on_n})}(-e^{At_{on_n}}(X_{N_n} - X_{eq_{on}}) - X_{eq_{on}}) - X_{eq_{off}}) + X_{eq_{off}} \\ &= X_{eq_{off}} - e^{A(T-2t_{a_n})}(X_{N_n} - X_{e_{on}}) - e^{A(T-2t_{a_n}-t_{on_n})}(X_{eq_{on}} + X_{eq_{off}}) \end{aligned} \tag{10}$$

About the second switch surface $X_{landing_n}$,

$$X_{landing_n} = -X(t_{on_n}) = -e^{At_{on_n}}(X_{N_n} - X_{eq_{on}}) - X_{eq_{on}} \tag{11}$$

2.2 Jerry's proof for pitch stability

3 Simulations

3.1 1 DOF Vertical Hopper with Open-loop Control[11]

System Setup

- Body mass $m = 1$ kg with massless leg, $l = 1$ m.
- Spring parameters: $\omega_n = 30$ rad/s, $\xi = 0.15$ (or equivalently, $kp = 900, kd = 9$)
- Static initial condition, COM height = 1.3 m (foot to ground = 0.3 m)
- Open-loop external force:

$$f_n(t) = \begin{cases} f_n \in \mathbb{C}, & \text{if } t \in t_{on}. \\ 0, & \text{otherwise.} \end{cases}$$

- t_{on}: The duration of actuator activation, starts when the spring reaches the maximum compression, ends when the contact point leave the ground.

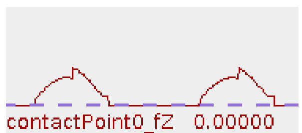

Figure 4: Ground reaction force when $f_n = 10$ N

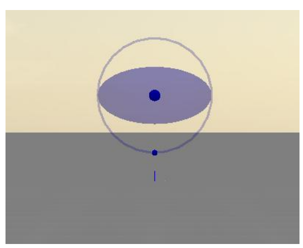

Figure 5: The vertical hopper, the blue dot at the bottom is the contact point of the massless leg.

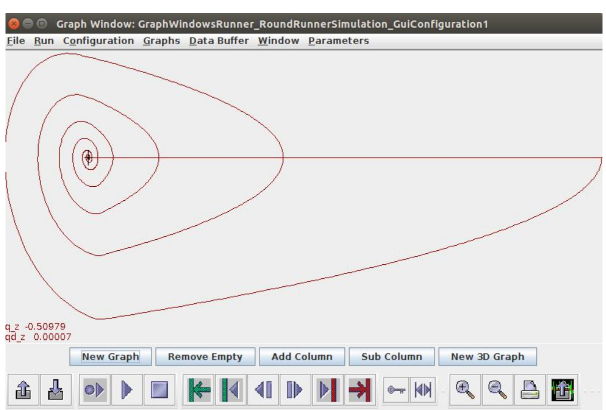

Figure 6: Phase portrait (stable spiral) of $f = 1$ N, period 0 sec

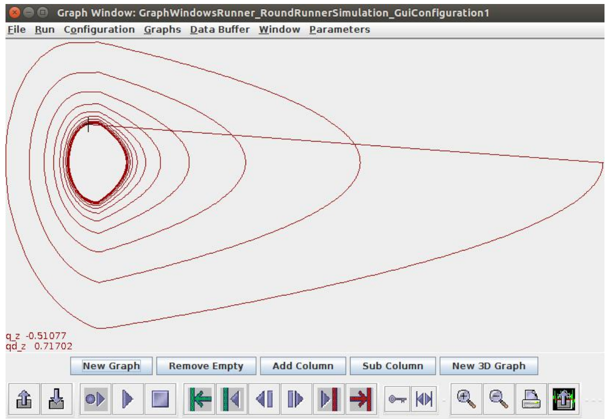

Figure 7: Phase portrait (stable limit cycle) of $f = 10$ N, period 0.27sec, (closer to the damped natural period $\approxeq 0.3295$ sec)

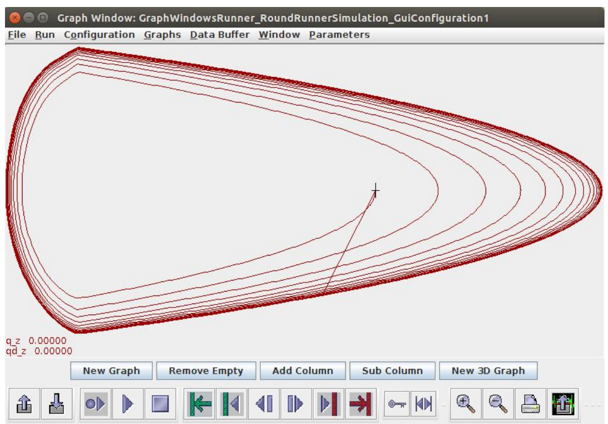

Figure 8: Phase portrait (stable limit cycle) of $f = 50$ N, period 0.859 sec

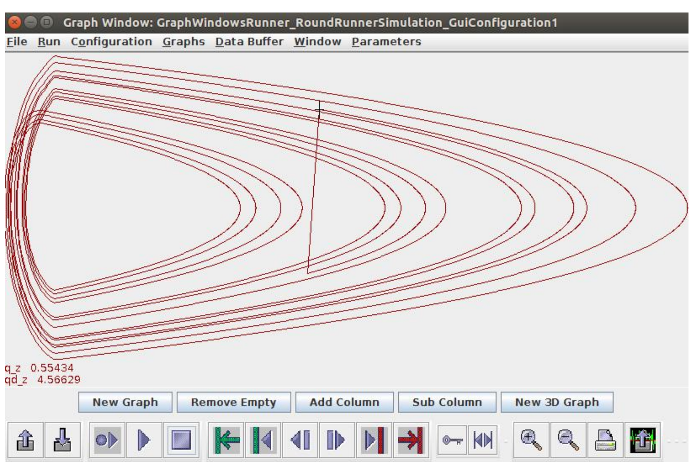

Figure 9: Phase portrait of $f = 100$ N, no stable limit cycle evolved (might be bifurcation).

Plan

- Go through and reuse the Poincare analysis in spokedRunner package.

- Could be a good case for me to learn how to use parameterOptimizer (or other constrained nonlienar program solver) to get IC/parameters for a stable/optimal gait.

3.2 Abstract Runner with Open-loop Normal Force and Closed-loop Pitch Angle Control

System Setup

- Body mass $m = 10$, $I_{yy} = 10$ with massless leg, $l = 1$.
- Reuse the vertical hopper above, change the initial condition to $\theta = 0.2$
- No force applied in the x direction, $\dot{x}_0$ can be 0 (hopper) or a constant (runner).
- Similar to the abstract runner (Fig. 10), enforces the on/off timing of ground reaction force $f_n(t)$:

$$f_n(t) = \begin{cases} (f_n + u) | f_n \in \mathbb{C}, & \text{if } t \in t_{on}. \\ 0, & \text{otherwise.} \end{cases}$$

where $f_n = \alpha * mg$, $\alpha \in \mathbb{C}$, u is the force from PD control, $kp_z = 80, kd_z = 6$. $kp_{pitch} = 80, kd_{pitch} = 6$

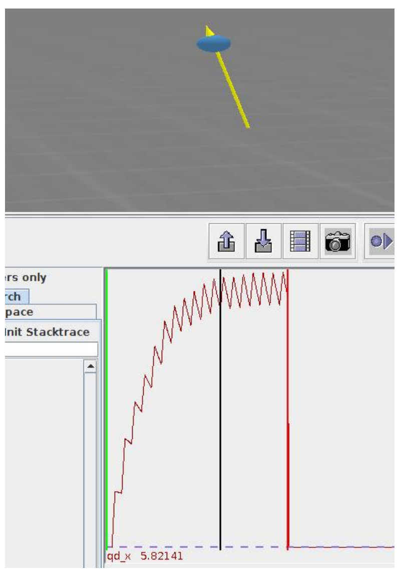

Figure 10: The Abstract Runner

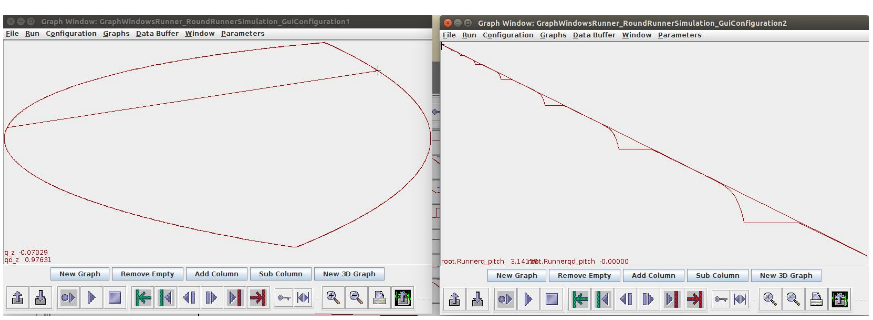

Figure 11: The phase portrait of the abstract runner: phase portrait (left) of body z movement $[q\_z, qd\_z]^T$ and the pitch motion (right, the movement is converging to the origin in the upper-left corner) .

Plan

- Link it to the Math from Jerry's note (analysis of a linear Poincare map) to get the boundaries of stable parameters.

3.3 Spoked Runner with Massless Legs

System Setup

- $m = 15$, $I_{yy} = 10$, $l = 4$, $r_{penetration} = 0.3$ (the distance the virtual wheel penetrate into the ground)
- Adjustable spoke leg number
- Fixed rotation rate w.r.t inertial frame
- Setup of contact force: PD control
  - w.r.t to world frame
  - w.r.t to inertial frame (virtual pivot point)
- Assuming no friction (Could be an bad idea?)

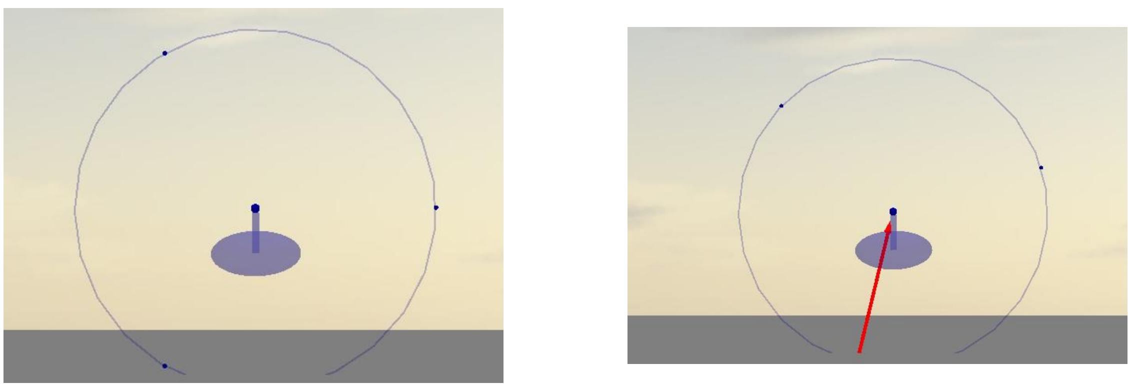

Figure 12: The Spoked Runner with three legs

Plan

- Smoothly change the leg length, or the rotational speed of the virtual wheel, and observe the system response.
- Learn how to use GUI for parameter adjustment with SCS.

4 Code implementation

4.1 Modeling and Parameters

Main idea: a virtual wheel (as the massless leg) with radius r_{wheel} penetrate the ground for a distance r_{pen} where a external force point pe is attached on it. A body (with mass m and inertia Iyy) is attached to the center of wheel. Using PD control to interpret contact force when p_e is under the ground.

06/07 First prototype (Not used now)

- Joint numbers: 2
- Joint types: Floating planer joint for virtual wheel and pin joint for the body link.
- Contact point type: External force point
- Virtual wheel rotation: set proper initial condition for virtual wheel (also need a large inertia to make it nearly constant).

Contact force: Assuming the ground height is 0,

$$F_z = kp(0 - pe_z) + kd(0 - ve_z) \tag{12}$$
$$\phi = atan2(pe_x, r_{wheel} - pe_z) \tag{13}$$
$$F_x = F_z tan(\phi) \tag{14}$$

where ve is the velocity vector of the contact point pe, kp and kd are the PD control parameters. F_x is calculated so that the vector of ground reaction force $[F_x, F_y, F_z]^T$ will point towards the virtual pivot (the center of the virtual wheel).

Assessments:

- Need to set a non-zero inertia of massless virtual wheel (for numerical stability), otherwise the simulation will diverge.
- The inertia of virtual wheel need to be a large one for constant rotational speed.
- Suggestions: remove the massless link, attach the external force point to the body and change its position in the controller every time step.

06/08 Round Runner

- Joint numbers: 1
- Joint types: Floating planer joint for the body link.
- Contact point type: External force point
- Virtual wheel rotation: Assigning the external force point location with respect to the joint in an open loop manner.
- Contact force: Assuming the ground height is 0,

$$F_z = kp(0 - pe_z) + kd(0 - ve_z) \tag{15}$$
$$\phi = atan2(pe_x, r_{wheel} - pe_z) \tag{16}$$
$$F_x = F_z tan(\phi) \tag{17}$$

  where ve is the velocity vector of the contact point pe, kp and kd are the PD control parameters. F_x is calculated so that the vector of ground reaction force $[F_x, F_y, F_z]^T$ will point towards the virtual pivot (the center of the virtual wheel).

Assessments:

- The ground reaction force looks better, while the energy is not balanced (after a while it will move towards the negative x direction)
- The inertia of virtual wheel need to be a large one for constant rotational speed.
- Suggestions: Use the ground contact point (instead of external force point) to see how it goes.

06/11 Round Runner(with Ground Contact Point)

- Joint numbers: 1
- Joint types: Floating planer joint for the body link.
- Contact point type: Ground contact point, linear contact model[1]
- Virtual wheel rotation: Assigning the external force point location with respect to the joint in an open loop manner.
- **Contact point number** Parameterized, currently set to 3-6 points.
- Contact force: using built-in functionalities, only assigning the kp, kd (PD parameters in the z direction), kp_x, and kd_x (PD parameters in the x/y directions).

Assessments:

- Was able to generate a stable walking. Contact point has sliding.
- Due to setting up stiffness and damping for x and z separately, the force is not always point towards the virtual pivot.

06/12 Round Runner(with External Contact Point Point)

- Implement the same one as 06/11, but replace the ground contact point to the external one (because it is more complex for ground contact point to adjust stiffness/damping as parameters.)
- implement the linear ground contact model basically.

06/13 Round Runner

- Parameterize contact point numbers
- Adding enum for switching between different setup: contact point type and the corresponding ground reaction force calculation: (w.r.t to the world frame or inertia frame.)

06/16 Round Runner (vertical hopper)

- Adding vertical hopper with open-loop force control
- Playing with open-loop force magnitudes for different stability conditions

[1] Disable the hardening stiffness in z direction by setting groundStiffeningLength to Double.NEGATIVE_INFINITY

5 Info might be useful

5.1 Going through references

1. Compare different terrestiral locomotions: Some parameters of the walk are not speed- dependent. The swing duration is a constant time parameter [1].
2. Trunk plays an important role during walking (birds) [2].
3. The use of these drives (Resonance drives, with adaptive control) allows increasing machine's quickness several times and decreasing energy expenses simultaneously 10-50 times [3].
4. Light weight leg (ostrich vs. moa) can run faster[5]. Also a famous allometric equation:

$$Y = M^{3/4} \tag{18}$$

   where M is the body mass, Y is the metabolic rate.
5. Human's walking may not be really self-optimized: the preferred speed maybe different from the energetically optimal speed[8].
6. It is concluded that the most important adjustment to the bodys spring system to accommodate higher stride frequencies is that leg spring becomes stiffer [19].
7. magic equations for imd force (ostrich) [26]
8. gait frequency was reported to be highly correlated with the resonant frequency of the mass-spring model [30]
9. WABIAN, why you are here? [31]

5.2 Categories

1. Nonlinear oscillators/components [3, 6, 9, 10, 12, 28, 39];
2. zoology, biomechanics of animals: [1, 2, 4, 5, 16]
3. Bio-inspired robots: [7, 32]
4. Reference I should read: [11, 15, 27, 28]
5. Article not found (or not free)[4].
6. Robots in 3D: [13]
7. Stability analysis (Monocycle, linearized system) [14] (Limit cycle) [11, 27] dimensionless [41]
8. Biology/Anatomical structure [17, 20]
9. Light weight fast robot [18, 25]
10. take a look again [21]
11. mechanism design of robot [22]
12. quadruped reference [23] MIT Cheetah[37]
13. human energy cost, resonance usage [24, 8, 38, 40]
14. walking parameterization [29, 21, 42]
15. human-animal differences [15]
16. open-loop robot [33], passive robot [35, 34, 36]

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