Using a Kinetic Model of Human Gait in Personal Navigation Systems

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Personal Navigation: Why?

- Personal navigation systems: Navigators that can be carried or worn by individuals
  - Primarily, generate a position solution.
  - Can provide velocity and attitude solution as well.
- Significant current interest in personal navigation systems for applications such as:
  - Location-based computing (e.g., cell phones, laptops, etc)
  - Assisted Living
  - Guidance for Visually impaired.
  - First responders (fire fighters, EMTs)
  - **Post surgery monitoring of patients**
  - **Law enforcement** & Military (e.g., urban navigation, cave navigation, etc.)
  - **Biometrics: Identify a person by gait.**

Guidance for the Visually Impaired

First Responder Navigation

Personal Navigation Solutions

- Most current personal navigation solutions are GPS-based.
  - Work well outdoors and away from urban canyons
  - Work poorly (or not at all) indoors
- Solutions based on other **position fixing** techniques are being explored.
  - Wi-Fi, Ultra Wide Band (UWB), Electro Optical/Infrared Cameras
  - Advantage: Position errors do not grow with time
  - Disadvantage: Infrastructure intensive
- **Dead reckoning** solutions are self contained and address some of the issues associated with position fixing systems
  - Step counting (pedometer) , shoe-mounted inertial navigation (NavShoe™ from Intersense), body-mounted inertial navigation.
  - Advantages: Self contained.
  - Disadvantages: Errors grow with time (“random walk”)

Inertial Navigation Systems (INS)

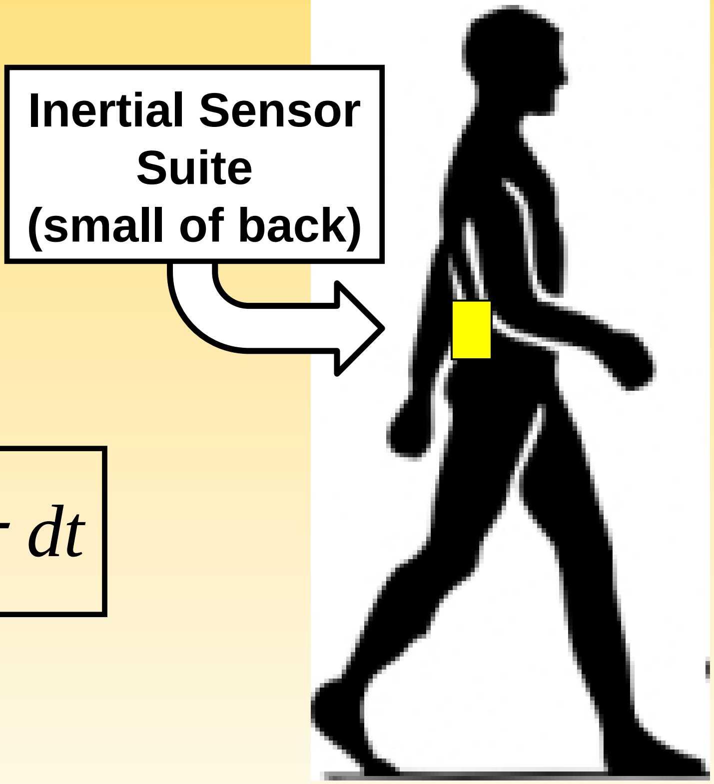
- Inertial Navigation Systems (INS): Self-contained navigators equipped with sensors continuously measuring acceleration ($\mathbf{a}$) and rotation/rotation rate ($\boldsymbol{\omega}$), from which velocity (v), position ($\mathbf{p}$) and attitude/orientation ($\mathbf{C}_n^b$) are computed.

$$\boxed{\mathbf{v} = \mathbf{v}_0 + \int_0^t \mathbf{a}\; dt}$$

Velocity Equation

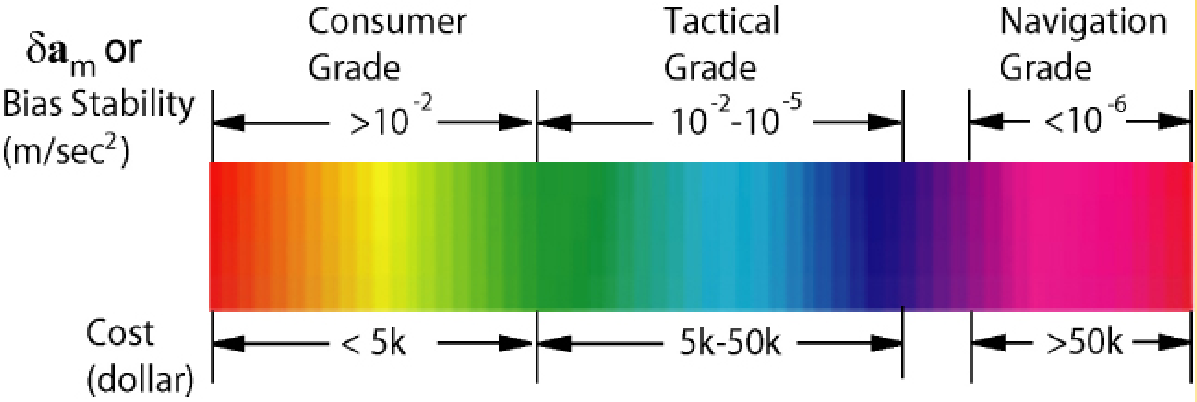
$$\boxed{\mathbf{p} = \mathbf{p}_0 + \int_0^t \mathbf{v}\; dt = \mathbf{p}_0 + \int_0^t \int_0^\tau \mathbf{a}\; d\tau\, dt}$$

Position Equation



Inertial Sensor Suite (small of back)

INS Quality Spectrum vs Error



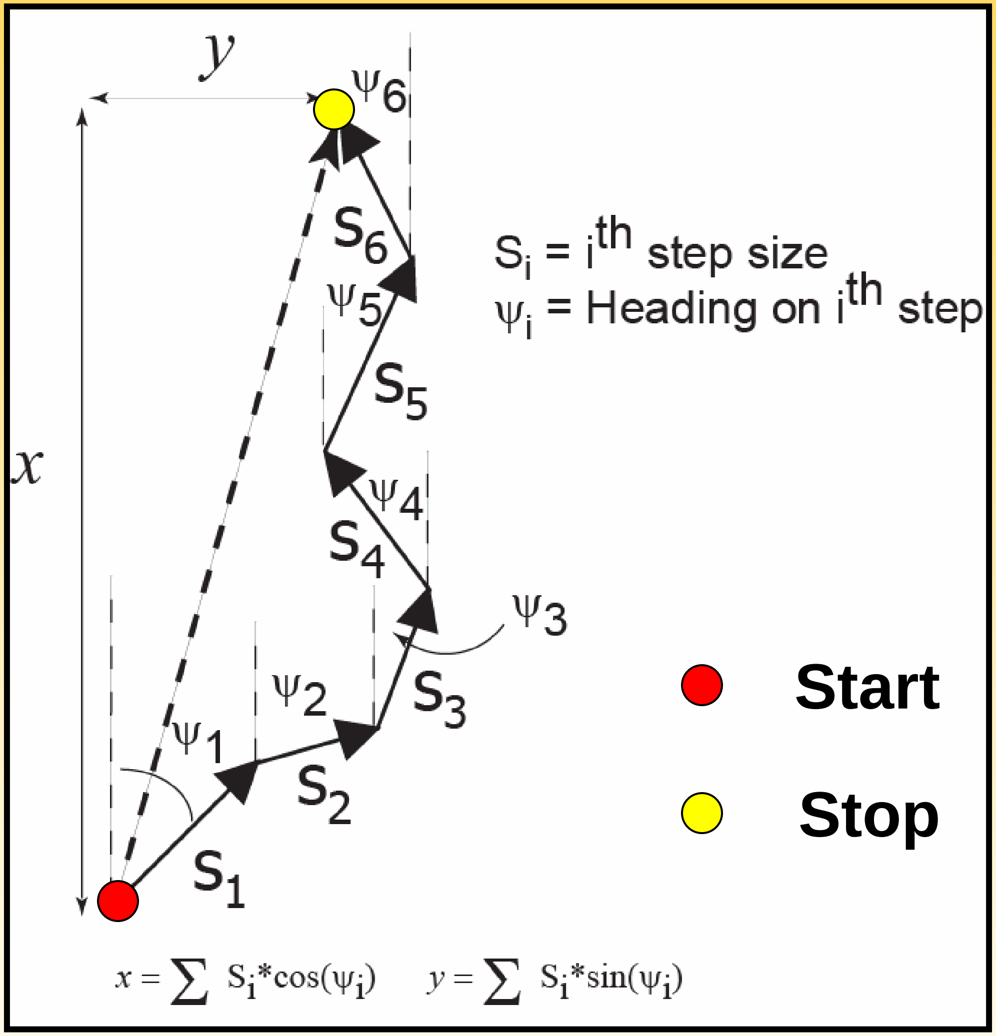
$$\mathbf{a}_m = \mathbf{a} + \delta\mathbf{a}$$

$$\begin{aligned}\hat{\mathbf{v}} &= \mathbf{v}_0 + \int_0^t \mathbf{a}_m \; dt \\ &= \mathbf{v}_0 + \int_0^t \mathbf{a} \; dt + \int_0^t \delta\mathbf{a} \; dt \\ &= \mathbf{v} + \delta\mathbf{v}(t)\end{aligned}$$

Bounding INS Drift with ZUPs

- Can use zero velocity updates (ZUPs) to bound position error drift
  - **V** at the end of each step is zero
- **Advantage**: Position error ($\Delta \mathbf{p}$) is becomes a linear function of time of travel (T) as opposed to a quadratic or cubic growth seen by traditional INS.
- **Problem**: Direction of travel or heading can be of poor quality if not aided by information from another source.

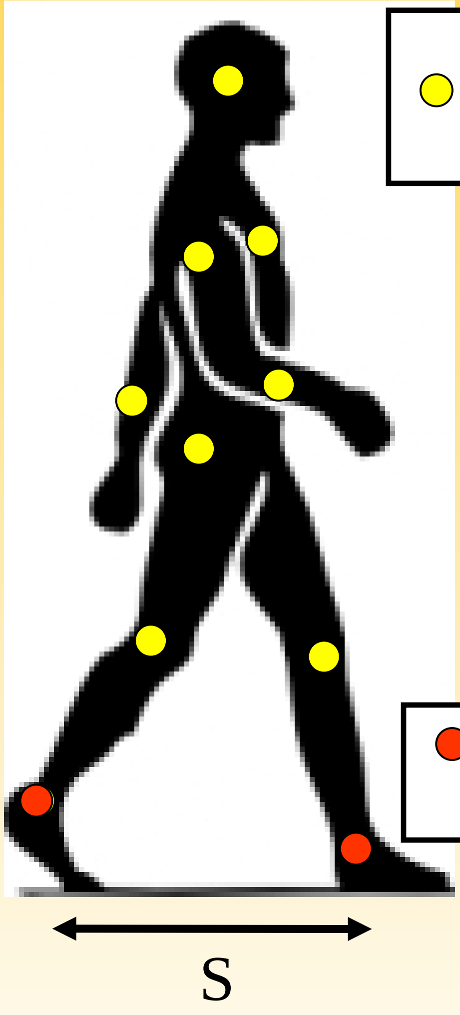
Step Counting (Pedometer)



$$x = \sum S_i * \cos(\psi_i) \qquad y = \sum S_i * \sin(\psi_i)$$

- Need a way to measure
  - The distance traveled during each step **(not a simple problem)**
  - The direction of travel (heading) during each step.
- Steps can be counted by using a sensor like an accelerometer.
- Direction of travel can be determined using a compass (magnetometer triad).

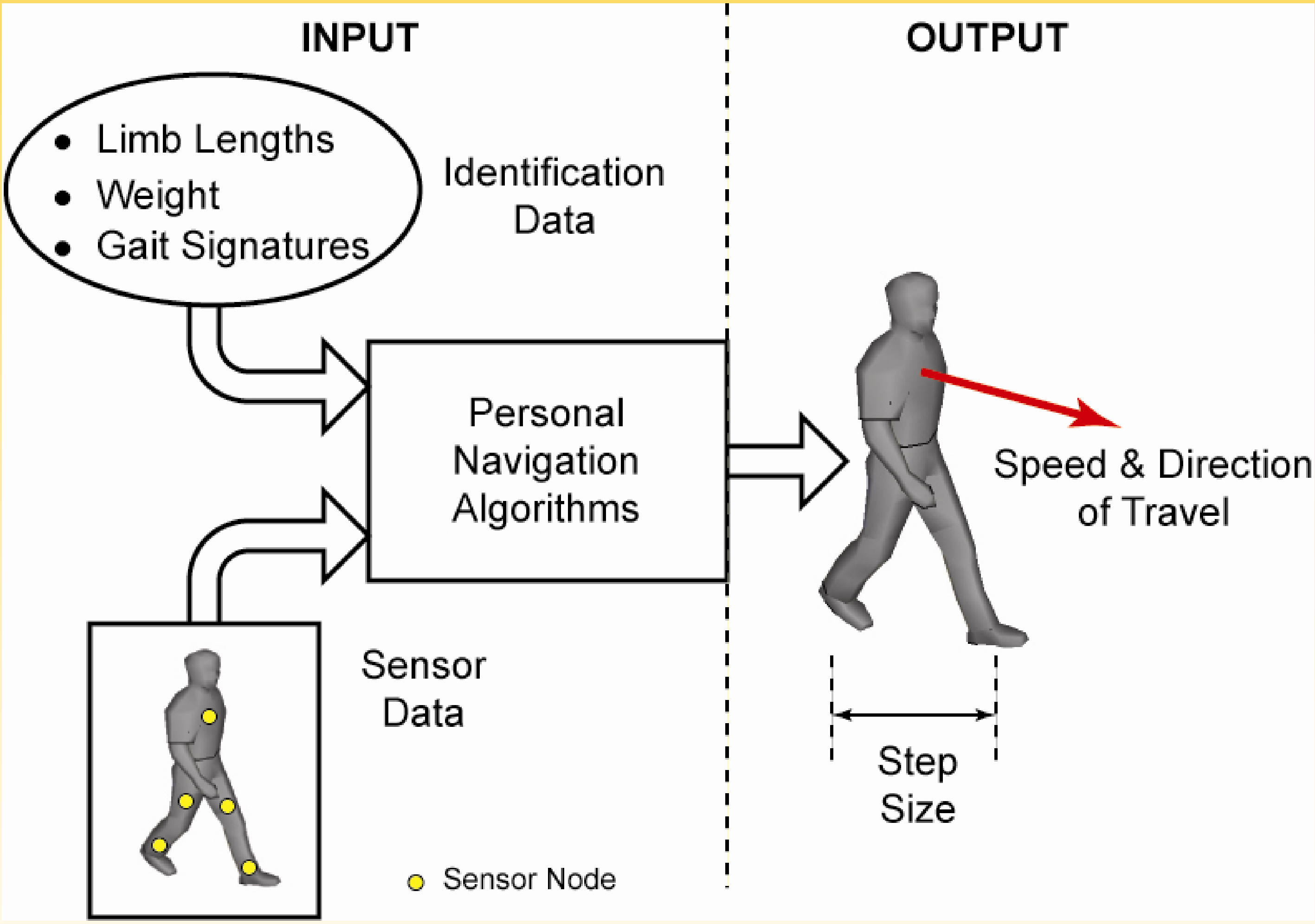
Motion Model: A Virtual Sensor?



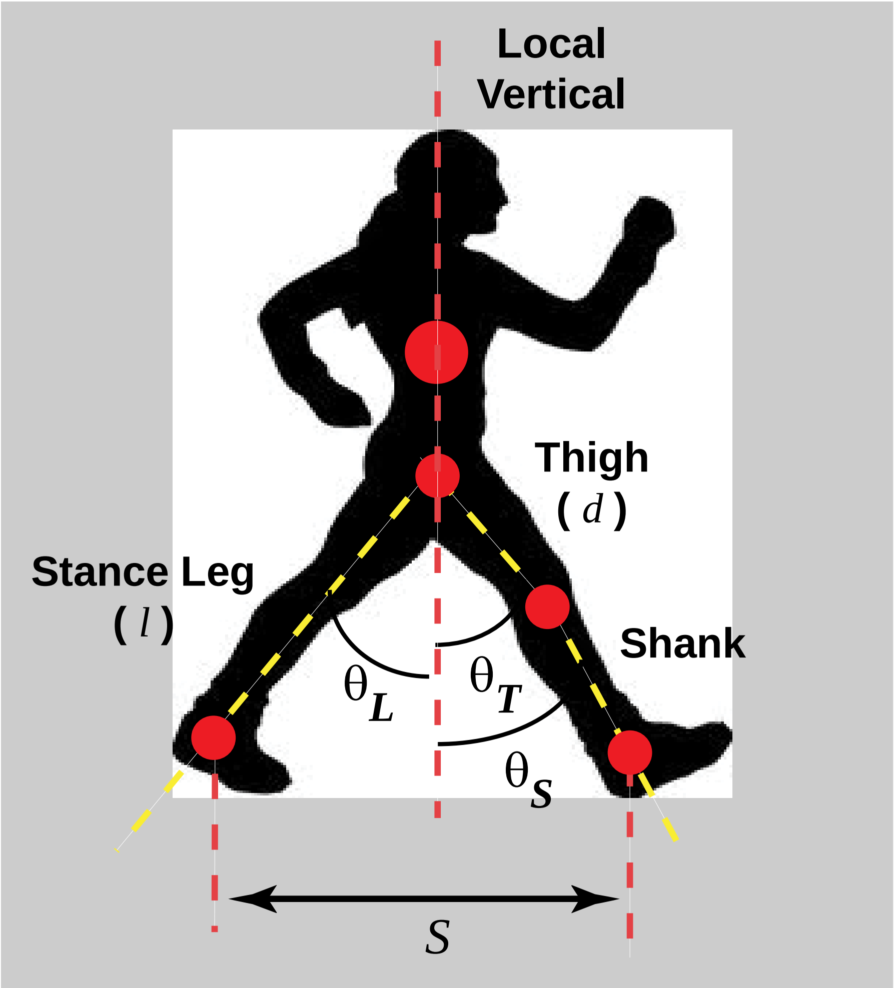
- Can knowledge of human motion be used as a **sensor or constraint** in personal navigation systems?
- What are the important parameters to characterize human motion (from a navigation point of view) ?

Yes. This talk is about using such models to estimate step size or S.

Proposed Approach



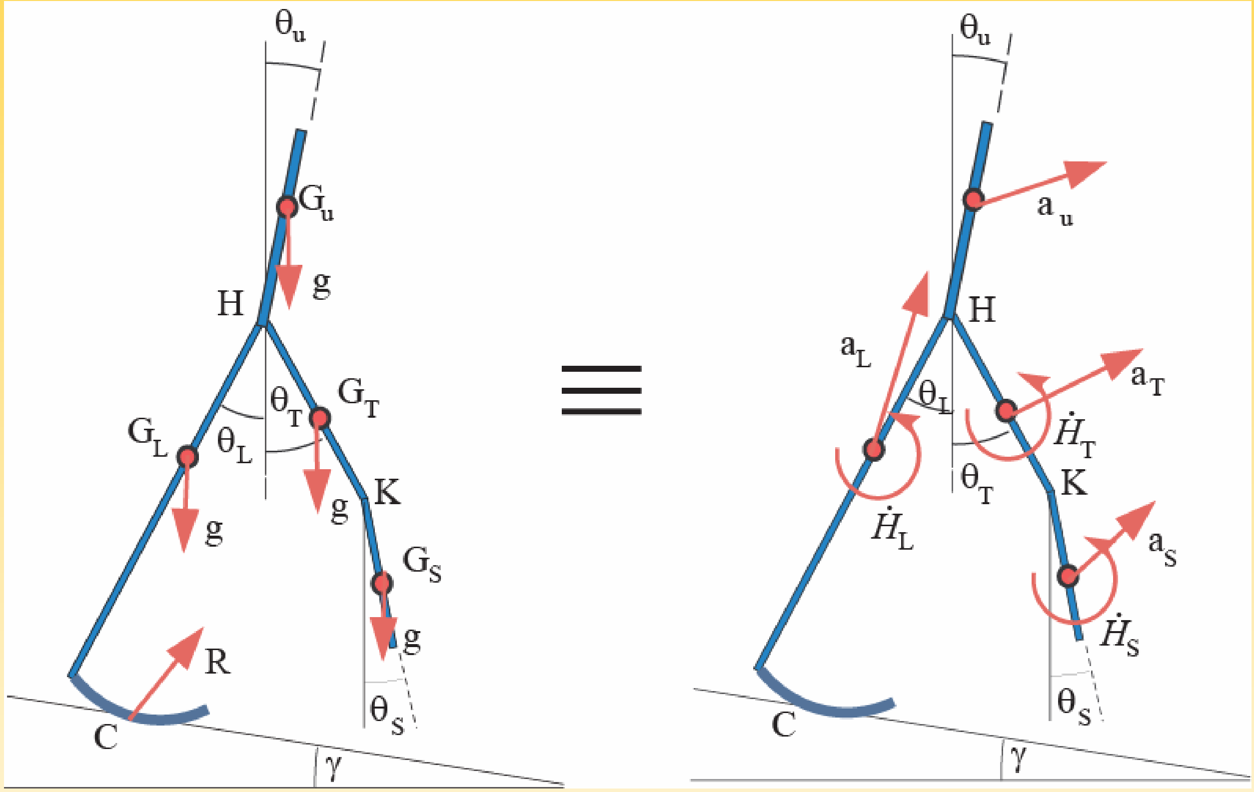
Step Size & Gait Kinematics



- Let us assume that we are dealing with a person walking in a straight line.
  - No heading change
- Let us also assume we are dealing with normal walking
  - No running, skipping, shuffling, etc.
- Then a time history of limb angles can be used to estimate step size (S).

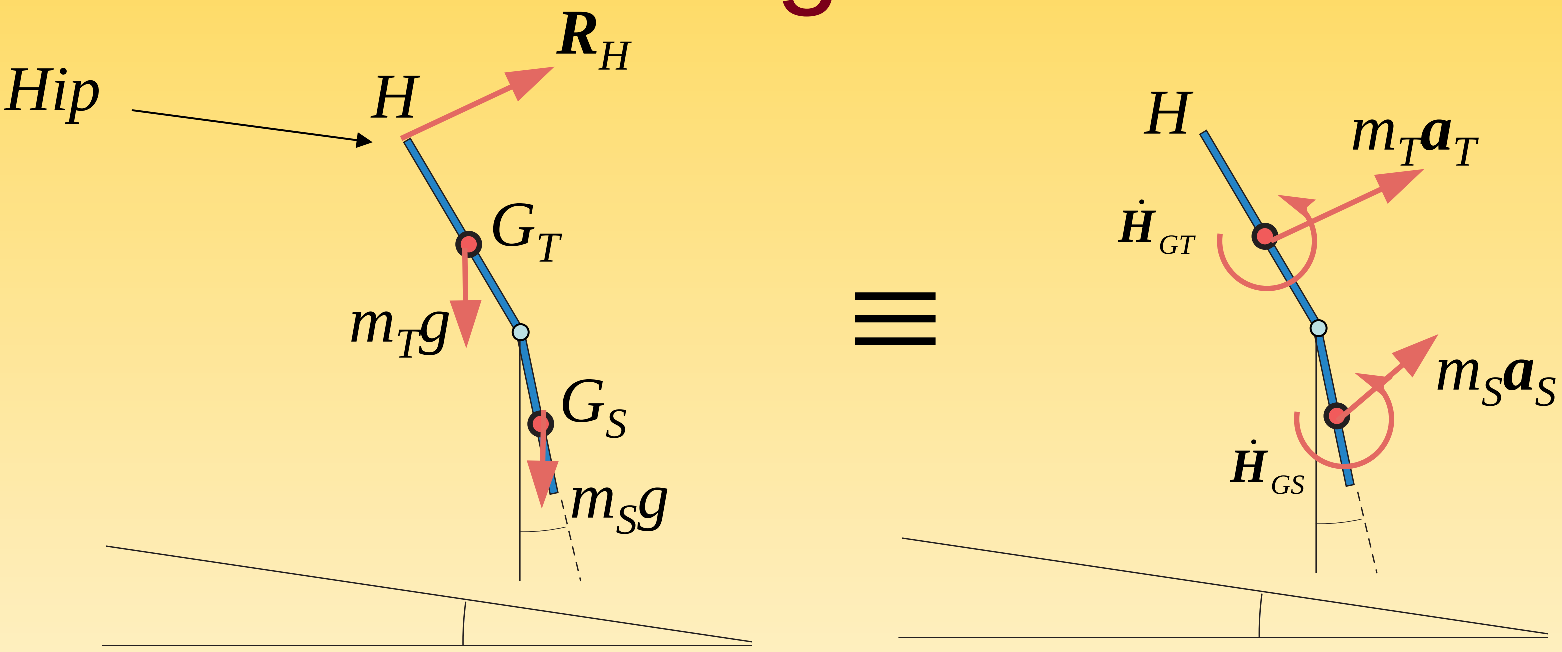
$$S = l\sin\theta_L + d\sin\theta_T + (l-d)\sin\theta_S$$

The Passive Walker



- The passive walker is an idealization of human gait.
- It assumes the motive force is gravity and ignores muscular inputs.

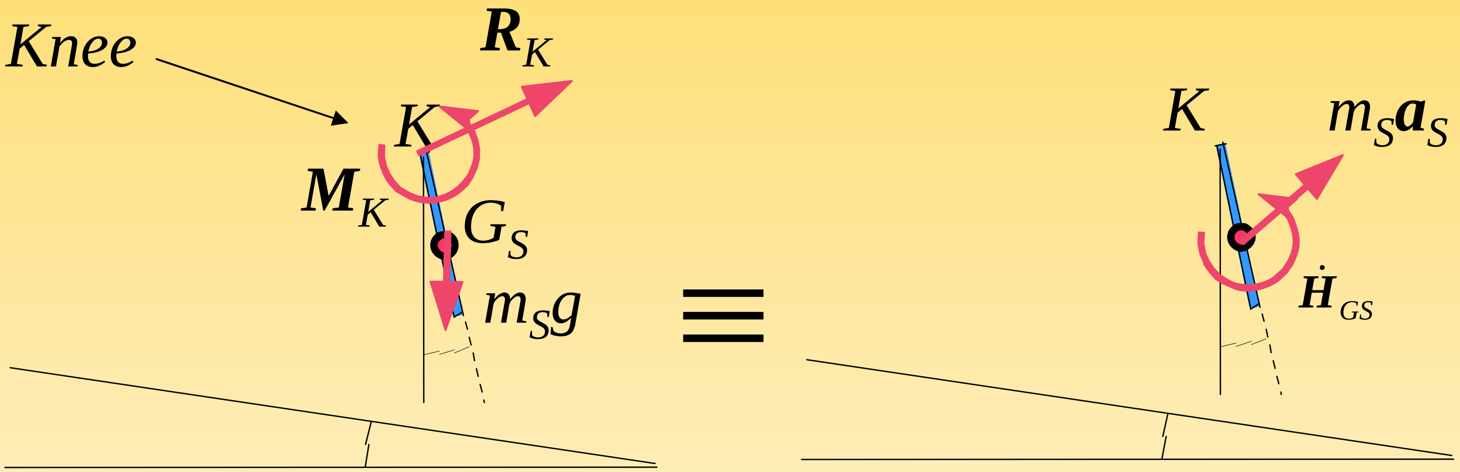
Thigh & Shank Free Body Diagrams



$$\sum \boldsymbol{M}_H : \quad \boldsymbol{r}_{HG_T} \times m_T \boldsymbol{g}_T + \boldsymbol{r}_{HG_S} \times m_S \boldsymbol{g}_S =$$

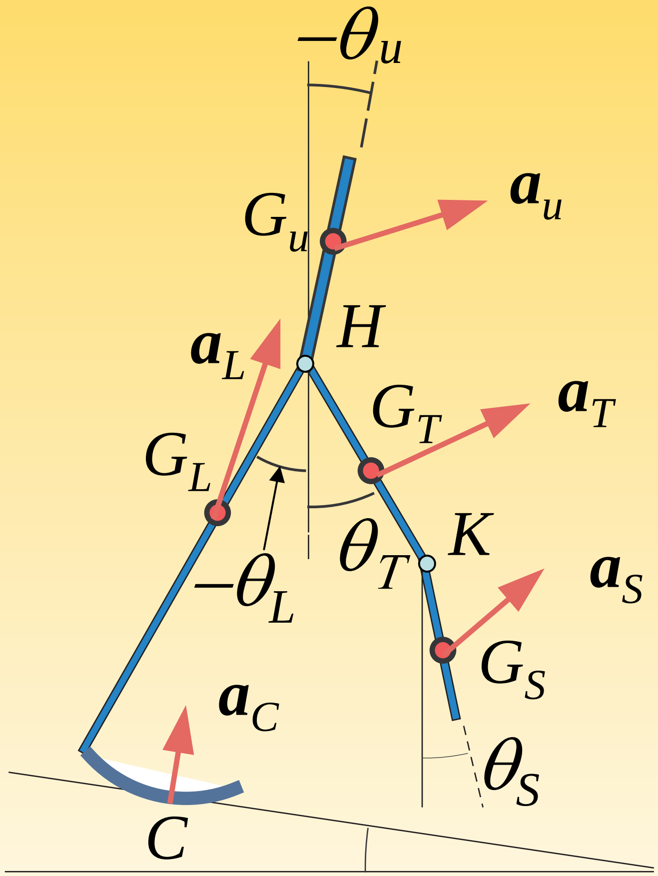
$$\bar{r}_{HG_T} \times m_T \boldsymbol{a}_T + \bar{r}_{HG_S} \times m_S \boldsymbol{a}_S + \dot{\boldsymbol{H}}_{GT} + \dot{\boldsymbol{H}}_{GS}$$

Shank Free Body Diagram



$$\sum \boldsymbol{M}_K : \boldsymbol{r}_{KG_S} \times m_S \boldsymbol{g}_S + \boldsymbol{M}_K = \bar{r}_{CG_S} \times m_S \boldsymbol{a}_S + \dot{\boldsymbol{H}}_{GS}$$

Passive Walker Kinematics



$$\boldsymbol{\omega}_L = \dot{\theta}_L \boldsymbol{k} \qquad \boldsymbol{\omega}_S = \dot{\theta}_S \boldsymbol{k}$$

$$\boldsymbol{\omega}_T = \dot{\theta}_T \boldsymbol{k} \qquad \dot{\theta}_u = \boldsymbol{0}$$

Ignoring Torso Sway

$$\boldsymbol{a}_{G_L} = \boldsymbol{a}_C + \dot{\boldsymbol{\omega}}_L \times \boldsymbol{r}_{CG_L} + \boldsymbol{\omega}_L \times \boldsymbol{\omega}_L \times \boldsymbol{r}_{CG_L}$$

$$\boldsymbol{a}_H = \boldsymbol{a}_C + \dot{\boldsymbol{\omega}}_L \times \boldsymbol{r}_{CH} + \boldsymbol{\omega}_L \times \boldsymbol{\omega}_L \times \boldsymbol{r}_{CH}$$

$$\boldsymbol{a}_u = \boldsymbol{a}_H$$

$$\boldsymbol{a}_{G_T} = \boldsymbol{a}_H + \dot{\boldsymbol{\omega}}_T \times \boldsymbol{r}_{HG_T} + \boldsymbol{\omega}_T \times \boldsymbol{\omega}_T \times \boldsymbol{r}_{HG_T}$$

$$\boldsymbol{a}_K = \boldsymbol{a}_H + \dot{\boldsymbol{\omega}}_T \times \boldsymbol{r}_{HK} + \boldsymbol{\omega}_T \times \boldsymbol{\omega}_T \times \boldsymbol{r}_{HK}$$

$$\boldsymbol{a}_{G_S} = \boldsymbol{a}_K + \dot{\boldsymbol{\omega}}_S \times \boldsymbol{r}_{KS} + \boldsymbol{\omega}_S \times \boldsymbol{\omega}_S \times \boldsymbol{r}_{KS}$$

Passive Walker Equations

- The passive walker equations from the previous slides can be recast into a the following form:

$$\mathbf{M}\ddot{\boldsymbol{\theta}} = \mathbf{A}\left(\dot{\boldsymbol{\theta}}, \boldsymbol{\theta}\right)$$

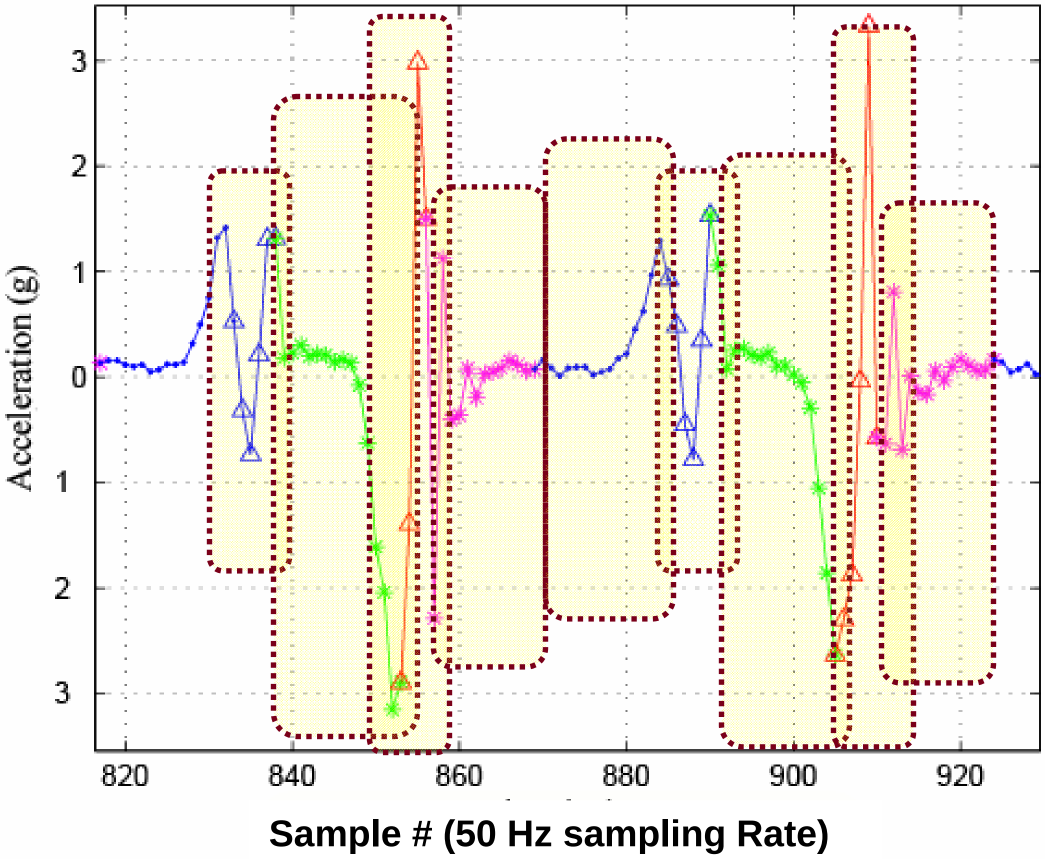
$$\ddot{\boldsymbol{\theta}} = \mathbf{M}^{-1}\mathbf{A}\left(\dot{\boldsymbol{\theta}}, \boldsymbol{\theta}\right)$$

$$\boldsymbol{\theta} = \begin{bmatrix} \theta_L & \theta_T & \theta_S \end{bmatrix}^T$$

- This form, in turn, can be recast in a non-linear, state-space form which looks like:

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\theta}_L \\ \dot{\omega}_L \\ \dot{\theta}_T \\ \dot{\omega}_T \\ \dot{\theta}_S \\ \dot{\omega}_S \end{bmatrix} = \mathbf{f}(\mathbf{x}) = \begin{bmatrix} \omega_L \\ G_1(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) \\ \omega_T \\ G_2(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) \\ \omega_S \\ G_3(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) \end{bmatrix}$$

Gait-Cycle: Ankle Acceleration



1. Pick Up and Go
2. Swing Phase
3. Impact
4. Weight Transfer
5. Stance Phase

Modified Passive Walker

- We can use the acceleration at the ankle ($\mathbf{a}$), input to the passive walker equations (an indirect measure of muscular torques)

$$\ddot{S} = \ddot{S}(\mathbf{a}) = \frac{d}{dt}\left(l\sin\theta_L + d\sin\theta_T + (l-d)\sin\theta_S\right)$$

- We also augment the state vector with an additional set of states to account for applied torques at the knee and ankle of the swing leg (assume quadratic over the step).

$$M_k = p_{k_0} + p_{k_1}t + p_{k_2}t^2$$

$$M_c = p_{c_0} + p_{c_1}t + p_{c_2}t^2$$

- The unknowns in these moment equations are the coefficients of the quadratic moment model.

Solving Modified PW Equations

- Given the initial conditions on angular velocities, we can use the accelerometer outputs to integrate the modified passive walker equations.

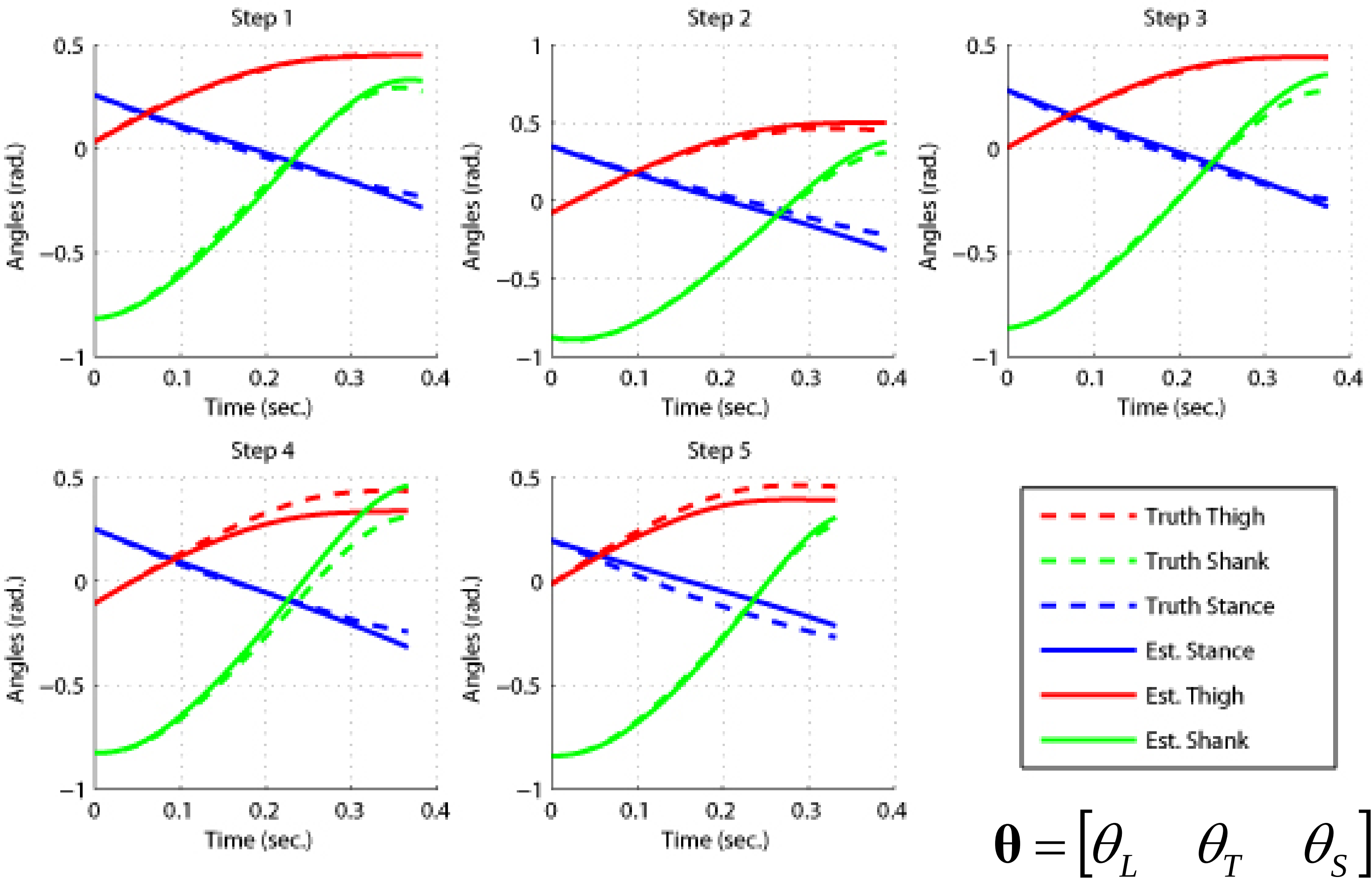
- What are the initial conditions?
  - For angles: we assume initial conditions for the current step are the angles at the end of the last step.
  - Angular rates: We solve for them.

- Basically, we solve an optimization problem
  - Unknowns are the initial conditions for angular rates and the moment coefficients
  - Solution is based on a set of terminal constraints.
    - Heuristic as well as physics based constraints
    - For example, the height of the foot at the end of the step should be zero.

Experimental Results

- One way we tested out results is by using data collected at the James R. Gage Center for Gait and Motion Analysis (Gillette Children's Hospital in St. Paul).
- Data collected from subjects walking in straight line and their motion was tracked using a Vicon™ motion tracking systems.
- Data was used to generate time history of limb kinematic states (position, velocity, accelerations, angular rates).
- Data was replayed in modified passive walker equations developed for this work.

Five Step Time History for θ



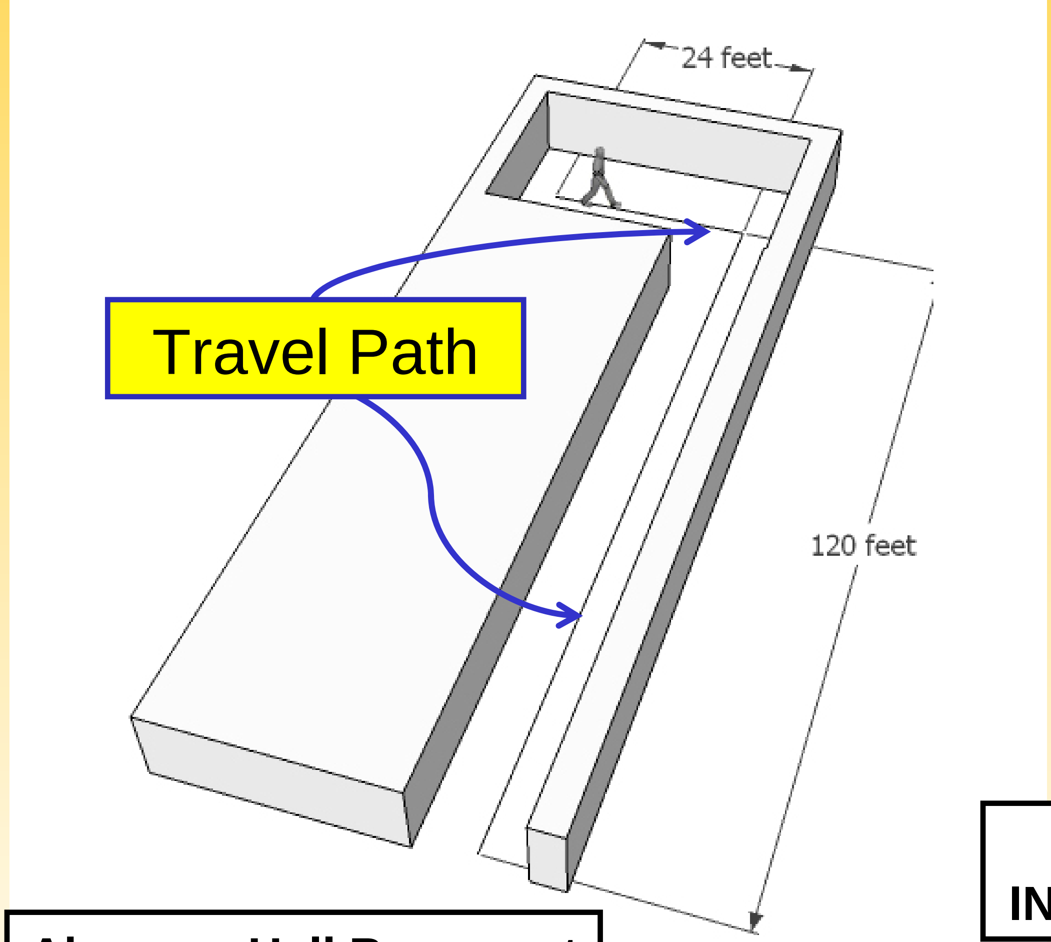
$$\boldsymbol{\theta} = \begin{bmatrix}\theta_L & \theta_T & \theta_S\end{bmatrix}^T$$

Step Counting Experiments

- Performed a series of experiments to assess the viability of estimating step size or stride length in-situ indoors.

- Subject (C. Matthews) had an IMU strapped to each ankle
  - MIDG II INS/GPS unit
  - Tile count/size provided truth reference while CPU time on the MIDG is used as the time base.

Basement Navigation Experiment



Akerman Hall Basement (Concrete Building)

MIDG II INS/GPS Unit

In-Situ Step Size Estimates

- Figures show that the model does a reasonable job of estimating the two varying step sizes (24” = 61 cm and 36” = 91.4 cm)
- Note that in this case, a measurement from a single accelerometer is used to augment the state vector:

Distance Traveled (Integrated Step Size)

Summary & Future Work

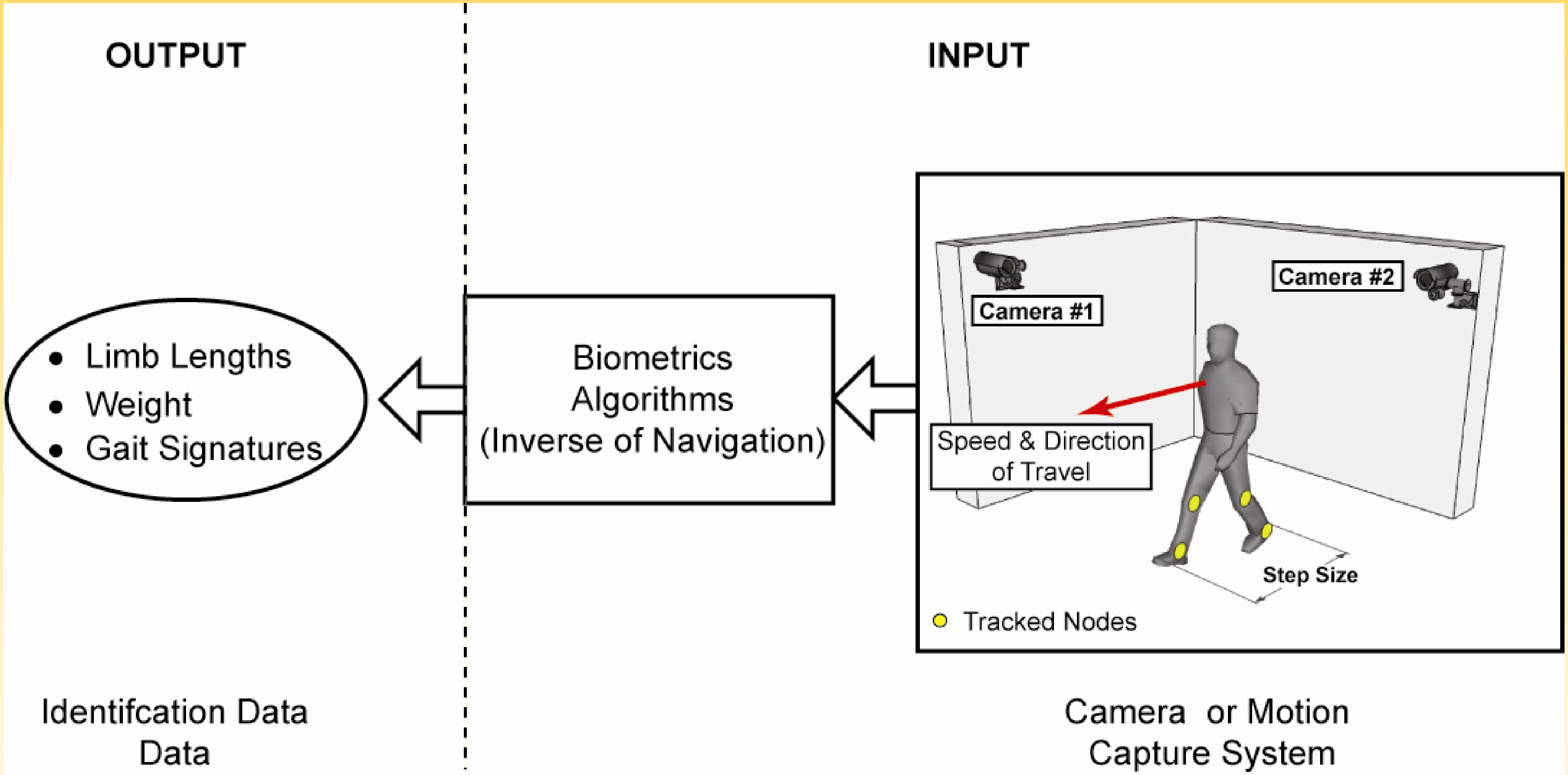
- Developed an approach for in-situ step size estimation (*c.f., C. J. Matthews, et al, "In-Situ Stride Length Estimation Using a Kinetic Model of Human Gait," ION-GNSS 2010*)

- Based on a kinetic model of gait and driven by a single acceleration measurement.
  - Adequate for "normal" step sizes
  - Cannot deal with turns or non-normal gait.

- On going work attempts to address turning motion as well as other non-normal gait patterns.

- Another thrust is to examine how gait characteristics can be used as means of identifying of persons.

Model Identification or Biometrics



OUTPUT

INPUT

- Limb Lengths
- Weight
- Gait Signatures

Biometrics
Algorithms
(Inverse of Navigation)

Identifcation Data
Data

Camera or Motion
Capture System

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