ALBIR: PDW SIMULATION COURSEWORK

1. Effect of varying ramp slope angles on the number of steps

The effect of the varying ramp slope angles on the number of steps taken by the Passive Dynamic Walker (PWD) was simulated on MATLAB for ramp angles between $3.0° - 8.0°$ with a step size of $0.1°$, an inter-leg angle of $60°$ and stance angle of $15°$. Figure 1 shows that the PWD maintains stability in the range $5.5° - 6.7°$ (see the red dots), with a peak of 7 steps occurring at $5.7°$ and $6.4°$.

- At lower angles of $3.0° - 4.1°$, the PDW halts, getting stuck and unable to move forward, which results in a lower step count. This is because the ramp angle doesn't provide sufficient gravitational force to overcome the resistance and generate the required leg swing for a forward momentum.
- Between $4.2° - 5.4°$, the walker takes two to three steps and then falls. The walker has enough room to complete a few leg swings as the gravitational force increases. However, the swing magnitude and the inter-leg angle rapidly decreases, and the walker tips forward, unable to fully overcome the resistance.
- At the peak/stable range, $5.5° - 6.5°$, the walker has a rhythmic inter-leg angle and stance oscillation, as seen in Figure 2b, allowing the walker to clock in higher number of steps. This is because an equilibrium is achieved as the passive dynamics of the walker are balanced by the gravitational force. At $6.4°$, the walker gradually halts near the end of the ramp as the inter-leg angle gets too wide for it to generate the next forward momentum, but at $5.7°$ it trips and falls.
- The discrepancies in the stable range, as seen at ramp angles $5.9°, 6.1° - 6.3°$, $6.6°$, might be due to some chaotic non-linear dynamics that cause instability at the boundaries. The walker stumbles and fall at times, unable to transfer its energy to the next steps efficiently. Further, the solver $ode23$ can also introduce variability. Thus, the stable region is extended to include $5.4° - 6.6°$ ramp angles.
- At higher angles of $6.7° - 8.0°$, the walker has excessive initial momentum due to the steep ramp angle that leads to imbalance and the walker falls forward with a low step count. Here, the centre of mass (CoM) of the walker crosses the line of gravity, experiencing the torque that causes is to tip over as seen in Figure 2c. (Physiopedia contributors, 2024.)

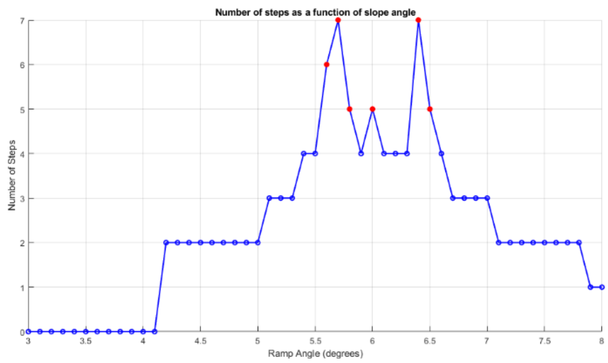
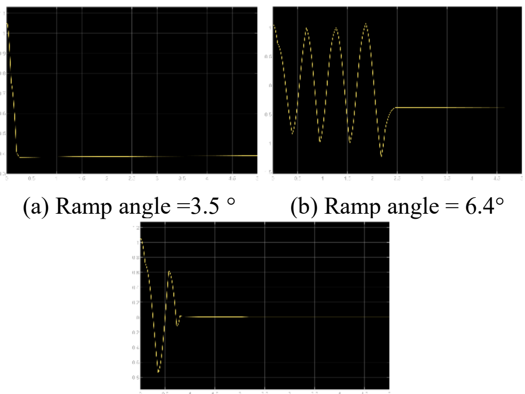


Figure 1: Number of steps taken by the PDW with varying slope (ramp) angles from 3° to 8°. Stable conditions (#steps>=5) are highlighted as red dots. The initial inter-leg angle is 60° and initial stance angle is 15°.



(a) Ramp angle =3.5 ° (b) Ramp angle = 6.4°

(c) Ramp angle = 7.0°

Figure 2: Inter-leg angles at different ramp angles.

2. Effect of varying initial inter-leg and stance angles on the number of steps

Next, the effect of varying initial inter-leg angles from $50°$ to $70°$ with a step of $0.5°$ and initial stance angles from $10°$ to $20°$ with a step of $0.25°$ on the number of steps taken by the PDW at a $6°$ ramp angle was assessed. A general bell-curve trend is seen across initial stance angles in Figure 3. For the initial inter-leg angles, it seems as if the chosen range is around the middle 68% of the bell-curve, and thus it has a lesser effect on the walker. Nonetheless, as seen in Figure 4, the green and yellow stable regions are concentrated at $60° - 65°$ initial inter-leg angles and $14° - 16°$ initial stance angles where the walker completes 11 steps before falling off the ramp. Here, the walker has an optimal energy equilibrium of gravity and resistance due to a good balance between the two angles, allowing for a consistent and rhythmic step cycle. The optimal conditions are stated in the caption of Figure 4. The blue regions depict the failed conditions with too high $[> 65°, > 18°]$ or low $[< 55°, < 12°]$ inter-leg and stance angles, respectively. At lower inter-leg angles the legs have insufficient momentum for a swing and the shallow stance causes an imbalance and the walker falls. At higher inter-leg and stance angles the swing is too wide, which places the walker in an awkward position where it is unable to proceed to the next step. It mostly gets stuck in a split leg position.

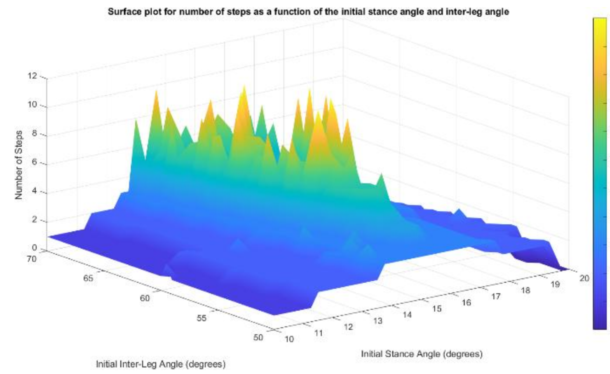


Figure 3: Surface plot for the number of steps taken by the PDW based on the varying inter-leg and stance angles at a ramp angle of 6°. Stable conditions observed in the green-yellow regions.

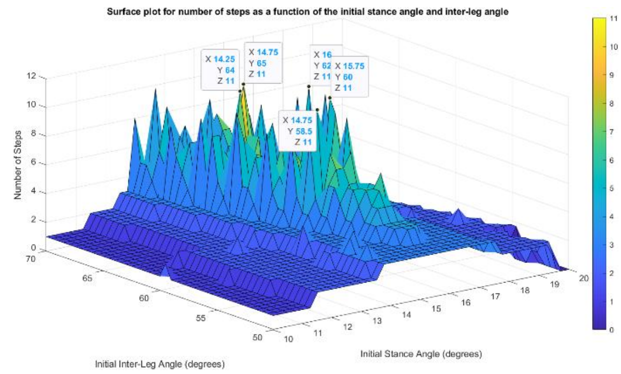


Figure 4: Annotated plot for question 2. Highest step count of 11 was observed at the following initial [inter-leg, stance] angle combinations: [58.5°,14.75°], [60.0°,15.75°], [62.0°,16°], [64.0°,14.25°] and [65.0°,14.75°]

3. Phase relationship of kinetic and potential energy during one simulation of PDW

At a ramp angle of 6°, initial inter-leg angle of 58° and initial stance angle of 15°, I used the centre of mass (CoM) trajectories (obtained from inertia sensor) to determine the potential energy (PE) and kinetic energy (KE) of the PDW over time. The CoM trajectories were first filtered at a lowpass cut off frequency of 12.5Hz with a second order Butterworth filter (Koltermann et al., 2018). The detrended PE was calculated using the formula $mass\ *\ gravity\ *\ height$, where height is the detrended z-axis and KE was computed using $\frac{1}{2} * mass * \sqrt{v_x^2 + v_y^2 + v_z^2}^{\,2}$, after smoothening the velocity (v) component. The heel strike events were calculated by taking the local minima of the CoM's z-axis (Figure 6). When manually corroborating these results, I observed that there are 2 additional heel-strike events at 1.2s and 1.7s, which might be due to the wide inter-leg angles and the leg bounce that introduce noise in gradient calculations. The first heel strike is when the walker is dropped on the ramp, losing PE and gaining KE, and the last 2 leg strikes after 2.5s are when the walker falls on the ramp with 0J KE and increasing PE, balancing the system's energies.

The sum of PE and KE is constant in an ideal mechanical system over time. Our case matches the theory as PE and KE are mostly out of phase, suggesting an energy transfer between the two. When the PDW raises its leg, we see a local peak in KE as the CoM increases. Next is the heel strike as the PDW brings the leg back down and then the local peak in PE as the CoM decreases. This is analogous to the natural pendulum-like motion, on which the PDW is based. The downward slope of the ramp results in varied timings, inter-leg angles and stance angles that affects the cyclical gait (Figure 6b), causing differences in the maxima of detrended PE in Figure 5. Further, the friction caused during the heel-strike causes the walker to lose its initial PE, which is why we get negative values and a gradual energy loss of the system over time.

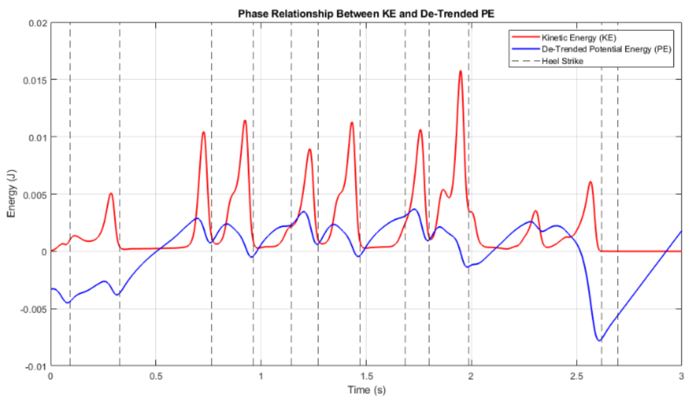
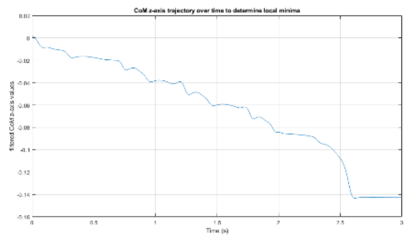
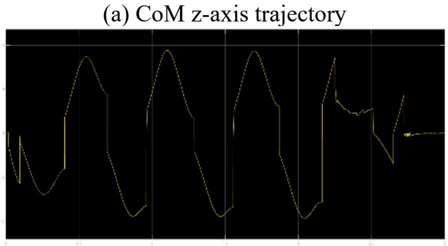


Figure 5: Phase relationship of detrended Potential Energy (PE) and Kinetic Energy (KE) using the walker's centre of mass (CoM) over time, with annotated heel strike events (vertical dashed black lines). Ramp angle = 6°, Stance Angle = 15°, Inter-leg Angle = 58°.



(a) CoM z-axis trajectory



(b) Inter-leg angle on scope

Figure 6: Heel-strike event calculations

I acknowledge the use of ChatGPT (OpenAI, https://chat.openai.com/) to understand the code and assignment. I confirm that no content generated by AI has been presented as my own work. I thank Prof Huai-Ti Lin and the GTAs, especially Ioana Lazar, for their help and support.