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Analysis of Combining Klann Mechanisms to Design a Walking Robot

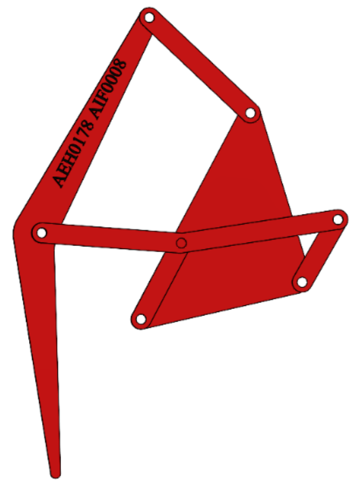

Figure 1: SolidWorks Model

The objective of this SolidWorks analysis is to measure data from a Klann mechanism which is shown in Figure 1. Later, eight of these mechanisms will be conjoined as a walking robot in order to understand the kinematic properties of the legs throughout the path traveled. In a Klann mechanism there are 5 different links that will be studied, links 2 through 6. Link 1 is omitted because its joints are fixed and do not move. In this Klann mechanism link 2 is the driving link that has a torque applied, link 3 is the coupler link, link 4 is the rocker crank, link 5 is the upper leg link and link 6 is the link that is used for the walking motion. These links can be found in Figure 2. Points O_2, O_4, and O_5 are all fixed and attached to the base, point A connects links 2 and 3, point B connects link 3 to link 4, point C connects link 3 to link 6, point D connects link 5 to link 6, point E is the contact point between link 6 and the ground, and lastly θ_2 is the angle of link 2 vs the x-axis. The forces that act on the Klann mechanism are the acceleration due to gravity acting on the linkage, F_g, the force of friction which prevents the mechanism from slipping on the ground, F_f, the contact force between the mechanism and the ground, F_c, and the torque of the motor, τ_2, which causes motion throughout the Klann linkage ultimately resulting in the walking motion from link 6.

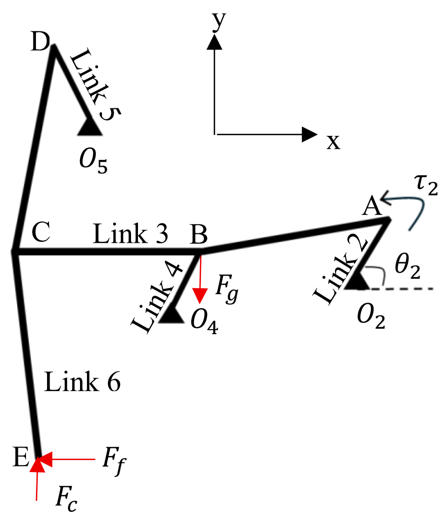

Figure 2: Free body Diagram of Klann Mechanism

Table 1 presents each link and their properties used in this exercise. To create this robot in SolidWorks, eight legs were connected to a base that has three different parts, each part weighs 10 lbm, this gives the whole assembly a combined weight of 37.2 lbm. Eight legs were used for stability and to have four touching the ground at a time, an angle mate was used to align them in the SolidWorks motion analysis. A four-legged robot was avoided since only two legs would be touching the ground at the same time causing the robot to be unstable. Klann mechanisms are extremely useful when the terrain is uneven and dangerous. The mechanisms are applied in robots used in search and rescue robots to maneuver rubble and in agriculture robots to avoid trampling crops.

Table 1: Link Properties

Link	Length (in)	Mass (lbm)	End Points
2	3.6	0.1	$O_2 - A$
3	7.92,7.00	0.2	A-B-C
4	4.3	0.1	$O_4 - B$
5	6.95	0.2	$O_5 - D$
6	12.05,12.05	0.3	D-C-E

The mechanism, analytically shown in Figure 2, rotates about O_2 with torque applied to crank link 2 counterclockwise. During this motion, trace paths of points B, C, D, and E are displayed in Figure 3. Points B and D only have an arcing motion which causes leg D-C-E to walk with point E touching the ground. The full movement of the leg walking is shown in points C and E with their full paths having a

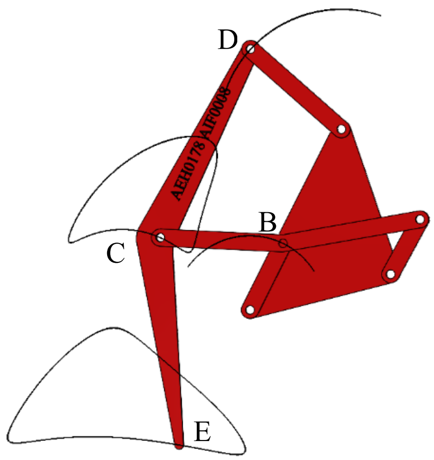

Figure 3: Model With Trace Paths

more triangular shape. Since this mechanism has links, velocities will have to go through vector addition since they are all relative to link 2. This addition can be shown physically with trace paths that are further away from O_2 by being larger on the ends of their links. The paths of B and C are one link away from link 2, with the torque, and show smaller and compressed trace paths. In contrast, paths D and E are two links away from link 2 and have larger and wider trace paths. These larger paths have higher velocities since they are affected by multiple other velocities on their link. Prior to displaying the calculations the following assumptions were made: the connection points between each moving link have no friction, the coefficient of static friction, μ_s, and the stiffness between the foot and the ground were set large, so no slipping or falling through the floor occurred, and the mass of any miscellaneous parts that were used to enhance creativity were set to 0. Last, the coefficient of static friction was set large enough, kinetic friction forces can be ignored. To find the force of friction the contact force is multiplied by μ_s as seen in equation 1.

$$F_f = F_c\mu_s \tag{1}$$

Newtons 2^{nd} law of motion seen is equations 2 and 3 are vital equations used to solve for the position vectors r_x, velocity vectors V_x, and acceleration vectors a_x of all points in Figure 2, x being the desired component. In equation 2 F_x is the force and m_x is the mass of a component. In equation 3 M_x is the moment, I_x is the inertia of a component, and α_x is the angular acceleration of a component, these terms will show up in future equations.

$$\sum F_x = m_x a_x \tag{2}$$

$$\sum M_x = I_x \alpha_x \tag{3}$$

Using rigid body kinematics, the relative position, velocity, and acceleration can be found for all points shown in Figure 2. A vector $\vec{r}_{x/y}$ is a position vector of point x relative to point y, this notation holds true for velocity,$\vec{V}_{x/y}$, and acceleration,$\vec{a}_{x/y}$, going forward.

$$\overrightarrow{r_A} = \overrightarrow{r_{O_2}} + \overrightarrow{r_{A/O_2}} \tag{4}$$

Equation 4 shows the position of point A relative to the stationary point O_2. To find the velocity, $\vec{V}_A$, of point A, the angular velocity, $\vec{\omega}_2$, of point 2, is used to take the cross product as seen in equation 3. For a particular link, angular velocity is shown as ω_x with subscript x being a point relative to Figure 2.

$$\overrightarrow{V_A} = \overrightarrow{\omega_2} \times \overrightarrow{r_{A/O_2}} \tag{5}$$

Equation 5 gives the velocity of point A, and the acceleration of point A is found and given in equation 6. The angular acceleration, α_2, of point 2 is also used for the acceleration of point A.

$$\overrightarrow{a_A} = \overrightarrow{\alpha_2} \times \overrightarrow{r_{A/O_2}} + \overrightarrow{\omega_2} \times \overrightarrow{V_A} \tag{6}$$

Link 2 is fully defined with the relative position, velocity, and acceleration equations. The rest of the links can be defined and are solved in equations 7 through 16.

$$\overrightarrow{V_B} = \overrightarrow{V_A} + \overrightarrow{\omega_3} \times \overrightarrow{r_{B/A}} \tag{7}$$

$$\overrightarrow{a_B} = \overrightarrow{a_A} + \overrightarrow{\alpha_3} \times \overrightarrow{r_{B/A}} + \overrightarrow{\omega_3} \times \left(\overrightarrow{\omega_3} \times \overrightarrow{r_{B/A}}\right) \tag{8}$$

$$\overrightarrow{V_B} = \overrightarrow{\omega_4} \times \overrightarrow{r_{B/O_4}} \tag{9}$$

$$\overrightarrow{a_B} = \overrightarrow{\alpha_4} \times \overrightarrow{r_{B/O_4}} + \overrightarrow{\omega_4} \times \left(\overrightarrow{\omega_4} \times \overrightarrow{r_{\frac{B}{O_4}}}\right) \tag{10}$$

$$\overrightarrow{V_c} = \overrightarrow{V_B} + \overrightarrow{\omega_3} \times \overrightarrow{r_{c/B}} \tag{11}$$

$$\overrightarrow{a_c} = \overrightarrow{a_B} + \overrightarrow{\alpha_3} \times \overrightarrow{r_{c/B}} + \overrightarrow{\omega_3} \times \left(\overrightarrow{\omega_3} \times \overrightarrow{r_{c/B}}\right) \tag{12}$$

$$\overrightarrow{V_D} = \overrightarrow{V_c} + \overrightarrow{\omega_5} \times \overrightarrow{r_{D/c}} \tag{13}$$

$$\overrightarrow{a_D} = \overrightarrow{a_c} + \overrightarrow{\alpha_5} \times \overrightarrow{r_{D/c}} + \overrightarrow{\omega_5} \times \left(\overrightarrow{\omega_5} \times \overrightarrow{r_{D/c}}\right) \tag{14}$$

$$\overrightarrow{V_E} = \overrightarrow{V_D} + \overrightarrow{\omega_6} \times \overrightarrow{r_{E/D}} \tag{15}$$

$$\overrightarrow{a_E} = \overrightarrow{a_D} + \overrightarrow{\alpha_6} \times \overrightarrow{r_{E/D}} + \overrightarrow{\omega_6} \times \left(\overrightarrow{\omega_6} \times \overrightarrow{r_{E/D}}\right) \tag{16}$$

Once the linear velocity and acceleration equations of point E are found, the motor torque can be found by choosing a velocity and acceleration for E and working backwards to find the motor torque given by equation 15 shown below. In the equation I_{O_2} is the mass moment of inertia of link 2, m_2 is the mass of link 2, $\overrightarrow{r_{G_2/O_2}}$ is the position vector of the center of gravity of link 2 with respect to O_2, and $\vec{g}$ is the acceleration of gravity.

$$\tau_2 = \left(I_{O_2}\alpha_2\right) + m_2\overrightarrow{r_{G_2/O_2}} \times \left(\overrightarrow{a_A} - \vec{g}\right) \tag{17}$$

Figure 4 presents the linear displacement of point E, the point in contact with the ground, versus the angle θ_2 of link 2. This point acts as a foot for the moving leg. When the slope is positive, the foot is rising to take a step, so it is not in contact with the ground. When the slope is negative the foot is pushing against the ground causing the forward movement of the robot. The minimum point of the graph is where the robot is about to rise up off the ground and the maximum point on the graph is where the leg is about to start pushing the robot forward.

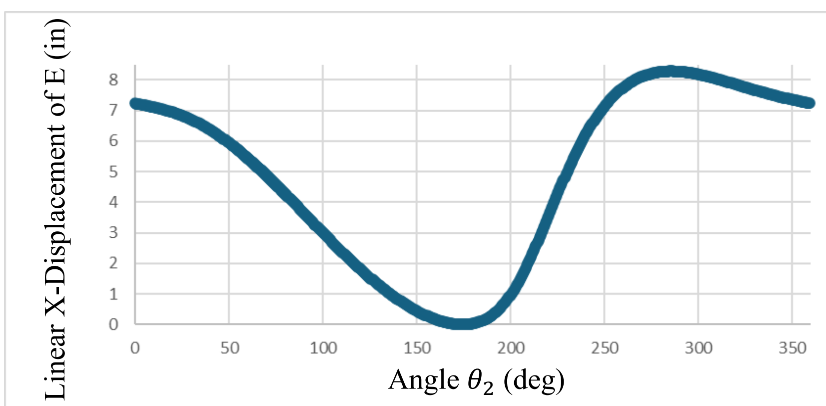

Figure 4: X displacement of E vs θ_2

Figure 5 shows the velocity as it relates to the motor speed applied. As the motor speed increases the velocity of the robot also increases and a line of best fit can be created as seen in equation 18, where V is the velocity and M is the motor speed.

$$V = 0.24M \qquad (18)$$

As the RPM of the motor increases the legs hit the ground more times, contributing to the increase in the velocity in the x axis.

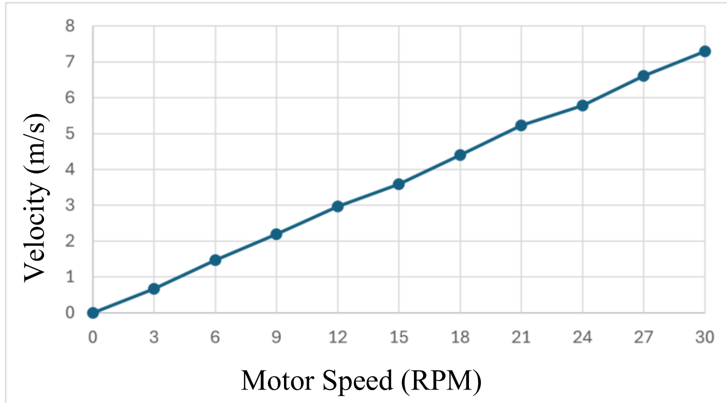

Figure 5: Average Velocity as a function of motor speed

Figures 6 and 7 represent how the torque on link 2 affects the robot's foot, point E, when it is lifted from the ground while walking. Figure 6 shows the robot's leg with only masses and gravity acting on it. When the motor link is straight and the foot is about to lift, the motor has to work harder to push the link and change the direction of link 4 which is shown in its short trace path on Figure 3. Figure 7 shows this same motion but with a normal force of 1lbf in the positive y and a friction force of 8lbf in the positive x. Instead of working harder when the links are straight, the friction force before the foot lifts from the ground and the normal force that's acting on point E promotes the motor having it go faster.

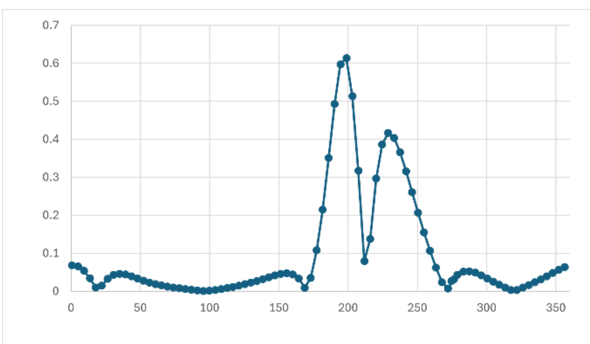

Figure 6: Motor Torque vs θ_2 no load

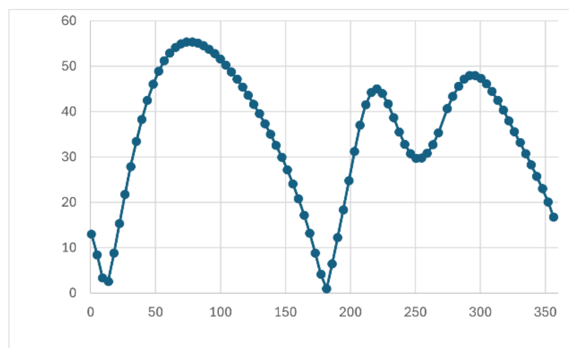

Figure 7: Motor Torque vs θ_2 with load

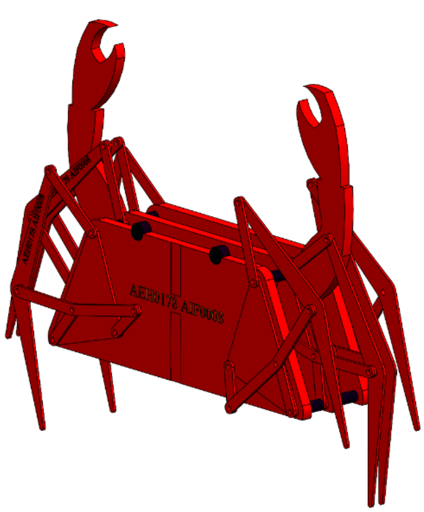

Figure 8: Completed Robot

Figure 8 displays the full robot that was designed. With the creative liberties that were given, a crab with eight legs was designed. One performance constraint that was faced during the making of this robot was the instability of having 4 legs. When the robot was made with 4 legs the minimum base width required so the robot would walk without tipping was 30 inches. To fix this 4 legs were added so there were always 4 legs in contact with the ground, this ensured stability while walking and prevented any tipping. One challenge that was faced was creating legs for the other side of the robot. If the leg from the original Klann mechaism was used the direction of the leg was incorrect, so another Klann mechanism was created except everything on it was mirrored to ensure each side had a correct facing leg.