Electronic Supplementary Material

Design methodology, synthesis, and control strategy of the high-speed planetary rover

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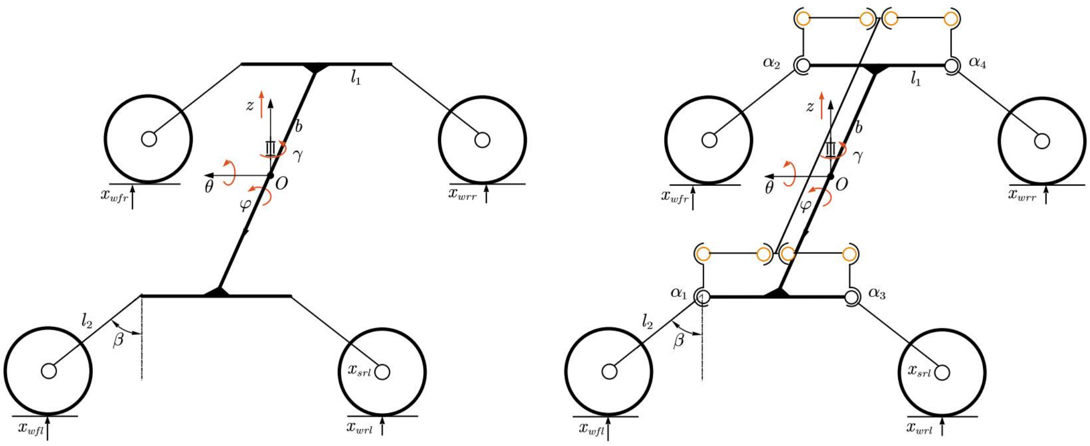
A. The all-wheel-attachment property for a multi-wheel rover

In this part, a rover without adaptive suspension and a rover with adaptive suspension are selected to analysis the significance of all-wheel-attachment property, which are shown as in Fig. A1.



(a) Rover without adaptive suspension (b) Rover with adaptive suspension

Fig. A1: Analysis of the significance of adaptive suspension

For the rover without adaptive suspension, the four wheel-ground contact points must be in the same plane, due to the unchangeable position between the wheels and the body. Therefore, the terrain to which this rover can be adapted is

$$x_{wfl} + x_{wrr} = x_{wfr} + x_{wrl} \text{ , (A1)}$$

Because the position between the wheels and the body can be changed, this condition is not suited for the rover with adaptive suspension. Similarly, at the dynamical level, this condition becomes

$$\ddot{x}_{wfl} + \ddot{x}_{wrr} = \ddot{x}_{wfr} + \ddot{x}_{wrl} \text{ , (A2)}$$

This condition can be changed when the system contains spring damper, but the spring damper has limited travel and is not a substitute for adaptive suspension. Therefore, a adaptive suspension is important for the HPR.

B. Derivation of the vibration equation for four-loop HPR

The notations of the four-loop rover are defined in Fig. B1. The vertical displacement, z, of the body, pitch, φ, and roll, θ angles of the body relative to the horizontal, angle of the synchronization-link, γ, relative to the body are selected as the generalized variables of the system. m denotes the mass of the body. I_φ and I_θ denote the pitch and roll inertia of the rover, respectively. I_γ is the inertia of synchronization-link. l_1 is half the distance between the two swing arm attachment points on the same side. $l_\beta = l_2 \sin\beta$, l_2 is the length of the swing arm on the outside of the body. β is the initial angle of the swing arm on the outside of the body, respect to the vertical direction. l_3 is the length of the swing arm on the inside of the body. x_{wfl}, x_{wfr}, x_{wrl}, x_{wrr} and $\dot{x}_{wfl}$, $\dot{x}_{wfr}$, $\dot{x}_{wrl}$, $\dot{x}_{wrr}$ are the displacement input and velocity input of road at four wheels.

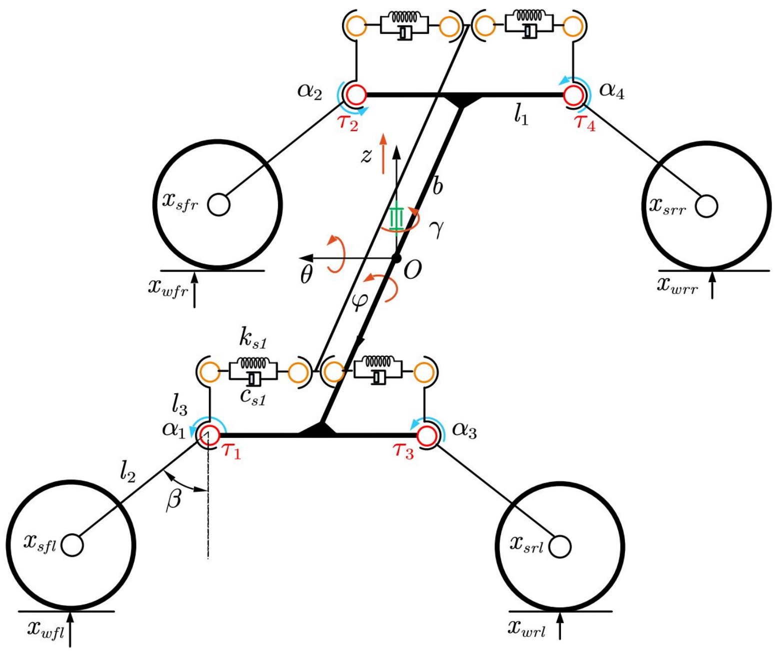


Fig. B1: Suspension type synthesis process based on SOC units

Assuming small angles of pitch and roll, the following equations are established:

$$\begin{cases} x_{sfl} + l_\beta(\varphi+\alpha_1) = z - l_1\varphi + b\theta \\ x_{sfr} + l_\beta(\varphi+\alpha_2) = z - l_1\varphi - b\theta \\ x_{srl} - l_\beta(\varphi+\alpha_3) = z + l_1\varphi + b\theta \\ x_{srr} - l_\beta(\varphi+\alpha_4) = z + l_1\varphi - b\theta \end{cases}, \text{(B1)}$$

The deformation variable of springs can be expressed as

$$\begin{cases} \Delta l_1 = l_3 \sin\alpha_1 + b\sin\gamma \doteq l_3\alpha_1 + b\gamma \\ \Delta l_2 = l_3 \sin\alpha_2 - b\sin\gamma \doteq l_3\alpha_2 - b\gamma \\ \Delta l_3 = l_3 \sin\alpha_3 + b\sin\gamma \doteq l_3\alpha_3 + b\gamma \\ \Delta l_4 = l_3 \sin\alpha_4 - b\sin\gamma \doteq l_3\alpha_4 - b\gamma \end{cases}, \text{(B2)}$$

The kinetic energy of the system can be expressed as

$$T = \frac{1}{2}m\dot{z}^2 + \frac{1}{2}I_\varphi\dot{\varphi}^2 + \frac{1}{2}I_\theta\dot{\theta}^2 + \frac{1}{2}I_\gamma\dot{\gamma}^2, \text{(B3)}$$

Combining Eq. (B.1) and (B.2), the potential energy of the system can be expressed as

$$P=\sum_{i=1}^{4}\frac{1}{2}k\left(\Delta l_i\right)^2$$
$$=\frac{1}{2}k\left(\left(l_3\alpha_1+b\gamma\right)^2+\left(l_3\alpha_2-b\gamma\right)^2+\left(l_3\alpha_3+b\gamma\right)^2+\left(l_3\alpha_4-b\gamma\right)^2\right)$$
$$=\frac{1}{2}k\left(\begin{array}{l}\left(l_{3/\beta}\left(z-\left(l_1+l_\beta\right)\varphi+b\theta-x_{sfl}\right)+b\gamma\right)^2+\left(l_{3/\beta}\left(z-\left(l_1+l_\beta\right)\varphi-b\theta-x_{sfr}\right)-b\gamma\right)^2\\+\left(l_{3/\beta}\left(z+\left(l_1+l_\beta\right)\varphi+b\theta-x_{srl}\right)-b\gamma\right)^2+\left(l_{3/\beta}\left(z+\left(l_1+l_\beta\right)\varphi-b\theta-x_{srr}\right)+b\gamma\right)^2\end{array}\right)$$, (B4)

The Lagrangian function can be expressed as L=T-P by combining Eq. (B.3)-(B.4) with the Lagrangian function. The derivative of the partial derivative of the generalized velocity and the derivative of the generalized position are

$$\begin{cases}\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial\dot{z}}\right)=m\ddot{z}\\\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial\dot{\varphi}}\right)=I_\varphi\ddot{\varphi}\\\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial\dot{\theta}}\right)=I_\theta\ddot{\theta}\\\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial\dot{\gamma}}\right)=I_\gamma\ddot{\gamma}\end{cases},\quad\begin{cases}\frac{\partial L}{\partial z}=-kl_{3/\beta}^2\left(4z-x_{wfl}-x_{wfr}-x_{wrl}-x_{wrr}\right)\\\frac{\partial L}{\partial\varphi}=-kl_{3/\beta}^2\left(l_1+l_\beta\right)\left(4\left(l_1+l_\beta\right)\varphi+x_{wfl}+x_{wfr}-x_{wrl}-x_{wrr}\right)\\\frac{\partial L}{\partial\theta}=-kl_{3/\beta}^2b\left(4b\theta-x_{wfl}+x_{wfr}-x_{wrl}+x_{wrr}\right)\\\frac{\partial L}{\partial\gamma}=-kb\left(4b\gamma-l_{3/\beta}x_{wfl}+l_{3/\beta}x_{wfr}+l_{3/\beta}x_{wrl}-l_{3/\beta}x_{wrr}\right)\end{cases}$$, (B5)

The generalized force is

$$\begin{cases}Q_z=-cl_{3/\beta}^2\left(4\dot{z}-\dot{x}_{wfl}-\dot{x}_{wfr}-\dot{x}_{wrl}-\dot{x}_{wrr}\right)+\left(\tau_1+\tau_2-\tau_3-\tau_4\right)/l_\beta\\Q_\varphi=-cl_{3/\beta}^2\left(l_1+l_\beta\right)\left(4\left(l_1+l_\beta\right)\dot{\varphi}+\dot{x}_{wfl}+\dot{x}_{wfr}-\dot{x}_{wrl}-\dot{x}_{wrr}\right)+\left(-\tau_1-\tau_2-\tau_3-\tau_4\right)\left(l_1+l_\beta\right)/l_\beta\\Q_\theta=-cl_{3/\beta}^2b\left(4b\theta-\dot{x}_{wfl}+\dot{x}_{wfr}-\dot{x}_{wrl}+\dot{x}_{wrr}\right)+\left(\tau_1-\tau_2-\tau_3+\tau_4\right)b/l_\beta\\Q_\gamma=-cb\left(4b\gamma-l_{3/\beta}\dot{x}_{wfl}+l_{3/\beta}\dot{x}_{wfr}+l_{3/\beta}\dot{x}_{wrl}-l_{3/\beta}\dot{x}_{wrr}\right)+\left(-\tau_1+\tau_2-\tau_3+\tau_4\right)b/l_3\end{cases}$$, (B6)

The vibration equation of the system is obtained as follows:

$$\boldsymbol{M}\ddot{\boldsymbol{x}}+\boldsymbol{C}\dot{\boldsymbol{x}}+\boldsymbol{K}\boldsymbol{x}=\boldsymbol{F}_p+\boldsymbol{F}_a$$, (B7)