APPENDIX

Jacobian matrics $\mathbf{H}$ and $\mathbf{D}$ in (17) are defined as:

$$\mathbf{H} = \left.\frac{\partial \mathbf{h}(\hat{\mathbf{x}} \boxplus \delta\mathbf{x}, \mathbf{0})}{\partial \delta\mathbf{x}}\right|_{\delta\mathbf{x}=\mathbf{0}} \quad \mathbf{D} = \left.\frac{\partial \mathbf{h}(\hat{\mathbf{x}}, \mathbf{n})}{\partial \mathbf{n}}\right|_{\mathbf{n}=\mathbf{0}} \tag{1}$$

Since $\delta\boldsymbol{\theta}$ is a small value between two consecutive steps, we apply following useful transformation:

$$\begin{aligned}\frac{\partial}{\partial\delta\boldsymbol{\theta}}\big(\mathbf{R}\mathrm{Exp}\,(\delta\boldsymbol{\theta})\,\mathbf{u}\big) \approx \frac{\partial}{\partial\delta\boldsymbol{\theta}}\mathbf{R}\big(\mathbf{I}+\delta\boldsymbol{\theta}^{\wedge}\big)\mathbf{u} &= \frac{\partial}{\partial\delta\boldsymbol{\theta}}(-\mathbf{R}\mathbf{u}^{\wedge}\delta\boldsymbol{\theta}) \\ &= -\mathbf{R}\mathbf{u}^{\wedge}\end{aligned} \tag{2}$$

where $\mathbf{u} \in \mathbb{R}^3$. By combining the (1) and (2), we can calculate the matrices of the individual measurement functions. For foot velocity measurement function (9):

$$\begin{aligned}\mathbf{H}_{FV} =& [-{}^{W}\hat{\mathbf{R}}(\hat{\boldsymbol{\omega}}^{\wedge}\,{}^{B}\mathbf{c}_i + {}^{B}\mathbf{v}_i)^{\wedge} \quad \mathbf{0}_{3\times3} \\ & \mathbf{I}_{3\times3} \quad \mathbf{0}_{3\times24} \quad -{}^{W}\hat{\mathbf{R}}{}^{B}\mathbf{c}_i^{\wedge}] \\ \mathbf{D}_{FV} =& \mathbf{I}_{3\times3}\end{aligned} \tag{3}$$

For i'th foot position measurement function (10):

$$\begin{aligned}\mathbf{H}_{FP} &= [\,({}^{W}\hat{\mathbf{R}}^{T}({}^{W}\hat{\mathbf{c}}_i - {}^{W}\hat{\mathbf{p}}))^{\wedge} \quad -{}^{W}\hat{\mathbf{R}}^{T} \\ &\quad \mathbf{0}_{3\times3i} \quad {}^{W}\hat{\mathbf{R}}^{T} \quad \mathbf{0}_{3\times3(9-i)}] \\ \mathbf{D}_{FP} &= \mathbf{I}_{3\times3}, \quad i \in [1,2,3,4]\end{aligned} \tag{4}$$

For i'th foot contact height measurement function (15)

$$\mathbf{H}_{CH} = [\mathbf{0}_{1\times3(2+i)} \;\; [0,0,1] \;\; \mathbf{0}_{1\times3(9-i)}], \quad \mathbf{D}_{CH} = 1 \tag{5}$$

For IMU measurements function (16):

$$\begin{aligned}\mathbf{H}_a &= [\mathbf{0}_{3\times21} \;\; \mathbf{I}_{3\times3} \;\; \mathbf{0}_{3\times6} \;\; \mathbf{I}_{3\times3} \;\; \mathbf{0}_{3\times3}] \\ \mathbf{H}_\omega &= [\mathbf{0}_{3\times24} \;\; \mathbf{I}_{3\times3} \;\; \mathbf{0}_{3\times6} \;\; \mathbf{I}_{3\times3}] \\ \mathbf{D}_a &= \mathbf{D}_\omega = \mathbf{I}_{3\times3}\end{aligned} \tag{6}$$