ATHLETE Mobility Performance with Active Terrain Compliance

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ATHLETE Software Development Models (SDM)

1st Generation SDM (2005)

- 2 Units: SDM-A, SDM-B
- ¼ Lunar scale
- ~7 ft full height
- 6-DOF limbs with wheels

2nd Generation SDM (2009)

- 1 Unit: SDM-T12
  - Splits into two 3-limbed Tri-ATHLETEs and deployable cargo pallet
- ½ Lunar scale
- ~13 ft full height
- 7-DOF limbs with wheels
ATHLETE Mobility

- Drive in benign terrain for speed and efficiency
- Walk in difficult terrain
- Minimal passive compliance

- Great capacity for complying to slopes and terrain when joints are actively controlled.
Active Terrain Compliance (1)

Multiple control objectives, calculated independently

- **Force distribution**
  - Compare $Z_{tool}$ force estimates to ideal distribution
  - Extend/retract wheel along $Z_{tool}$ axis to reduce deviation
  - For extreme deviation, reduce drive speed to accommodate limb adjustments

- **Transverse Load Reduction**
  - Terrain interactions lead to accumulated limb deflection
  - Detected as nonzero $Y_{tool}$ force
  - Adjust steering to reduce limb deflection

- **Wheel Speed Synchronization**
  - Monitor for wheels lagging behind the commanded wheel rate profile
  - Retract wheel along $Z_{tool}$ axis to reduce loading

- **Deck Leveling**
  - Monitor IMU for tilt deviation
  - Extend/retract wheels along $Z_{tool}$ axis to correct tilt

- **Deck Centering**
  - Adjust wheel positions along $X_{tool}$ and $Y_{tool}$ axes to center deck over footprint

- **Deck Height Management**
  - Extend/retract wheels along $Z_{tool}$ axis to maintain desired deck height
Active Terrain Compliance (2)

- Correction magnitudes selected via linear interpolation
  - \( D \geq D_{\text{max}} \) gets maximum correction, \( C = C_{\text{max}} \)
  - \( D \leq D_{\text{min}} \) gets minimum correction, \( C = C_{\text{min}} \)
  - \( D_{\text{min}} < D < D_{\text{max}} \) gets interpolated correction \( C_{\text{min}} < C < C_{\text{max}} \)

![Graph showing correction vs deviation with \( C_{\text{max}} \) and \( C_{\text{min}} \) levels at different deviations \( D_{\text{min}} \) and \( D_{\text{max}} \).]
Active Terrain Compliance (3)

- Correction components combined into an overall position and orientation goal.
- New goals applied at 2 Hz

\[
\begin{align*}
\begin{bmatrix}
    x_{\text{goal}} \\
    y_{\text{goal}} \\
    z_{\text{goal}} \\
    \text{roll}_{\text{goal}} \\
    \text{pitch}_{\text{goal}} \\
    \text{yaw}_{\text{goal}}
\end{bmatrix}
& =
\begin{bmatrix}
    x_{\text{now}} + x_{\text{center}} \\
    y_{\text{now}} + y_{\text{center}} \\
    z_{\text{now}} + z_{\text{force}} + z_{\text{level}} + z_{\text{height}} \\
    0 \\
    0 \\
    yaw_{\text{now}} + yaw_{\text{yload}}
\end{bmatrix}
\end{align*}
\]
Field Results: JPL Mars Yard 2006 (1)

No Active Compliance

Wheel forces (normal) for ATHLETE A on 12/03/2007

- Limbs start evenly loaded at ~1800 N
- Forces diverge by ~2000 N after driving 25m on benign terrain
SDM-A with Active Compliance

- Limb forces converge when AC engaged
- Over bumpy, rutted terrain, forces vary but do not diverge
Long traverses using Active Compliance

Wheel forces (normal) for ATHLETE B on 06/11/2008

- 8.8 km traversed by SDM-A & SDM-B with cargo over rolling sand dunes
- Limb forces reliably maintained near nominal 2300 N

Low-force spikes indicate limb lifted to refresh force estimate or reposition
Driving SDM-T12 with Active Compliance

- Limb forces converge to nominal ~2800 N when AC is used
- Force variation increases with increased terrain relief, but doesn’t diverge
Active Compliance 5-leg force distribution

- Forces distributed evenly during 6-wheel driving
- With leg 5 lifted, algorithm maintains uneven distribution – greater nominal loading for legs 4 and 6.
Conclusions

• Active Terrain Compliance
  – Effectively controls limb loading and vehicle pose on all existing ATHLETE prototypes
  – Has enabled traverses of >1 km per day over rolling natural terrain
  – Is effective for both symmetrical and asymmetrical loading conditions

• Future Work includes adapting the algorithm for a wider range of driving conditions
  – Longer traverse distances
  – Higher ground speeds
  – Improved slope-climbing capability
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