Reconfiguring Linkage Robots with Active and Passive Modules

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Active/Passive Model

- active units contain two rotating grippers (4DOF total)
- extend to 3D by adding “twist” DOF
- passive units are 1D bars: reliable, strong, easily fabricated
- applications: payload transport on trusses, truss assembly and inspection, active truss structures
A Continuum of Modular Linkages

- Simple: one climbing module
- Complex: $k$ climbing and self-articulating modules
- $n$ self-assembling modules
- $n$ self-articulating modules
Context and Related Work

Rotational Reconfiguring

- High-DOF/closed-chain non-topological (kinematic) mobility underexplored
- Very few systems include fully passive modules

Bi-Partite Modular

Hyper-Redundant

- Topological reconfiguration often not included
- Existing work does not unify climbing, self-assembly, and structure mobility
- Hierarchical kinematic control underexamined

Variable Geometry Truss

Truss Climbing
The Shady Climbing Robot

- 3.4kg total, ~1m dia. deployable sun shade
- climbs vertical planar truss at ~1cm/s
- 7.2A-h 7.4V LiPo, over 6h climbing/chg
- fully untethered, bluetooth radio comm
Proprioception for Reliability

• previous version
  – relied on exteroception: optical bar detection, tactile pressure sensors
  – incidental compliances only
  – grippers required modification to truss
  – only 80% reliable

• hypothesis: replace exteroception with proprioception and intentional compliances to improve reliability

• new version based on proprioception
  – 99.8% reliable
Mechanical Compliances

- gripper rotation motors torsion mounted
- spring rotation sensed, forming an SEA
- stiffness ~0.6N-m/°

- central sprung hinge
- biases grippers towards truss
- stiffness ~0.4N-m/°
Wide Opening Grippers

- pair of 6-bar linkages, each of which is two coupled 4-bars
- opens to nearly 3x width of truss bar, while retracting behind fairing
- in singularity when gripped—high grip force, non-backdriveable
- silicone rubber grip pads w/ about 46N (measured) grip force
- ± 13° rotation of closing gripper and ± 3° supporting gripper tolerated
- corresponds to about 4.2cm translational misalignment tolerance
- opens in about 7s, closes in about 15s
Proprioceptive Grip Refinement

1. gripper initially misaligned
2. close gripper
3. rotation compliances & wide gripper opening accommodate misalignment
4. in-plane misalignment may induce normal-direction walk-off
5. sense gripped configuration
6. adjust actuators to maintain sensed config
7. re-grip
8. central sprung hinge pushes gripper towards truss, eliminating walk-off
Measuring Reliability

- executed 1296 individual grip/ungrip/rotate motions on the window
- including horizontal and vertical locomotion and all orientations of transition
- over 6h of climbing
- only two faults, both non-dangerous & remotely recovered (possible cause: intermittent fault in encoder interface circuit)
- 99.8% of motions successful
- odometric slip of about 0.01% apparent but only for certain sequences
3D Hardware Results
$n$-Module Simulations
Hierarchical Control for Self-Assembly

- above group-level controllers instantiated repeatedly for $n$ groups
- top-level controller creates, commands, and coordinates individual group controllers
Hierarchical Control for Mobility

• two-layers of control: individual block-tilt controller, high-level chain controller
• block tilt controller gives entire 9-unit block a single tilt abstraction
• damped-least-squares IK chain controller moves chain given EE command
• chain controller assumes only the tilt abstraction
  ➢ works for blocks of different types

• simple example—hierarchy could be extended to more layers
• prior meta-module research focused on topological shape-reconfiguration
  ➢ we also address open and closed-chain kinematic mobility
3D Meta-Module Assembly & Mobility

[You receive a diagram of a 3D meta-module assembly]
Summary

• a continuum of active/passive modular linkage systems
• minimalist approach: 4DOF in 2D, 5DOF in 3D
• applications: structure assembly and inspection, active/mobile structures
• mechanical compliances and proprioceptive control accommodate uncertainty
  ➢ 99.8% reliable climbing
• algorithms/simulation of hierarchical control for self-assembly/mobility

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