SUMMARY

This thesis presents energy invariant mechanisms that can be scaled to micro size. They are also called statically balanced, because all static forces are balanced against each other. They enable effortless suspension of weight, and flexible devices without stiffness, seemingly defeating gravity and elasticity. In large scale applications such as movable bridges and ship lifts gravitational forces dominate elastic forces and counterweight balancing is the only practical approach. At small length scales, roles reverse: gravity becomes insignificant and elastic forces dominate. While other conservative forces such as magnetics or electrostatics also become relevant, focus will be placed on elastic forces.

Static balancing is investigated at various scales, working our way down as we progress through the chapters. This investigation starts with a method for the analysis and synthesis of energy invariance in rigid body mechanisms, which are often used to aid the more difficult design of compliant mechanisms. It allows symbolic derivation of balancing conditions for serial kinematic chains with any number of links and zero-free-length springs. Virtual transmissions are introduced to temporarily constrain the chain to single degree of freedom and ease solving. Examples are provided in 2D and 3D.

Static balancing is commonly used in civil engineering, robotics and large scale compliant mechanisms, where preloading is relatively easily applied by hand or preloading assembly. However, preloading becomes difficult at small scales and is identified as the primary reason the state of the art is not down-scalable. It is addressed by the design of various monolithic and planar architectures. The fully compliant mechanisms with linear and rotary motion incorporate a bistable mechanism that sustains the required preload in a reversible way. In one case, opposing constant force and torque achieves stiffness reduction by 98.5 % and 90.5 % respectively with increased relative range of motion (from 3.3 % to 6.6 %) and reduced complexity compared to the state of the art.

In the second case a new V-shape plate spring is used that minimizes and maximizes stiffness when preloaded and when not preloaded respectively. An unprecedented stiffness reduction of 99.9 % and 98.5 % is achieved under large deformations in fused model deposition prototypes made out of polylactic acid. In all four cases switching between soft and hard modes can be done reversibly by toggling the bistable switch directly. Alternatively, the soft mode can be entered by actuating the shuttle over a force threshold.

In addition, preloading is addressed by making it part of the manufacturing process by exploiting residual stress from thin film deposition. A stiffness reduction by a factor 9 to 46 is achieved over a range of 380 µm by thermal oxidation of silicon. The stiffness reduction is achieved in a passive way, allows for parallelized manufacturing, is space efficient and is scalable, since surface effects become more dominant at smaller scales.

Miniature statically balanced mechanisms will be an enabling technology for low frequency sensors, mechanical energy harvesting, mechanical watch oscillators, mechanical logic and computing, microrobotics, compliant transmission mechanisms, and make small scale compliant mechanisms more energy efficient.