Mobile robots are generally required to pass through non-flat terrains which may contain holes and obstacles. Robots which are adequate for performing this task are limbed robots. The goal of this research is to navigate a multi-limbed robot under gravitational field effects. The navigation of the robot is achieved by quasistatic gaiting. In quasistatic motion, inertial effects due to moving parts of the robot are kept small relative to gravity forces and forces of interaction with the environment.

The navigation of multi-limbed mechanisms in two dimensions using quasistatic motion was studied by [1], [2]. However, gravitational field effects were not included. Or and Rimon [3] characterized robust equilibrium postures in a two-dimensional gravitational field where the mechanism was modeled as a single rigid body. In this work, however, we are concerned with the analysis of stable equilibrium stances while accounting for the compliance induced by the mechanism's joints.

A planar spider-like robot is described. The robot consists of an unactuated central base which is attached to \( k \) limbs. Each limb consists of \( n \) links and \( n \) actuated revolute joints. The robot thus has a total of \( k \cdot n + 3 \) degrees of freedom. We assume that the robot's footpads contact a piecewise linear terrain with known geometry and that each contact is frictional with a known lower bound on the coefficient of friction.

We use a stiffness control law proposed by Salisbury [4] to induce a desired stiffness at each contact point. Known stiffness at the contacts allows determination of the contact forces. We obtain an analytic expression for the location of the robot's equilibrium points according to the stiffness induced by the control law. The stability of each equilibrium point is then analyzed. In addition, we present the constraints on the location of the robot's center of gravity. These constraints ensure that each contact point would not slip. Assuming Coulomb's friction model, each contact force must therefore lie within its respective friction cone. The constraints must also ensure that the footpads would not break contact with the terrain. Therefore, the normal reaction force on each footpad must be positive. We present the feasible region where the center of gravity must be located. The feasible region is formed by
the above constraints. Locating the center of gravity outside the feasible region i.e., violation of one or more of the constraints may result in destabilizing the robot and therefore causing the robot to fall. Navigation is achieved by moving the robot through a sequence of postures such that the robot's center of gravity remains within the feasible region, and thus maintains stable equilibrium during motion.

Experiments are conducted to verify the stability of the robot's equilibrium stance. The robot used in the experiments is shown in figure 1. It was developed for navigating in two-dimensional tunnel environments [2]. The robot's design was based on [5]. It consists of three limbs attached to a central base. Each limb consists of four revolute joints. Therefore, the robot has a total of 15 degrees of freedom. Each joint is actuated by a DC motor and each joint's value is measured by an optical encoder. The robot's response to small perturbations is measured and analyzed, and experimental results are reported.

![Figure 1: Experimental 3-legged robot](image)

**References**


