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Review article

# Snake robots☆

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A B S T R A C T

The inspiration for snake robots comes from biological snakes. Snakes display superior mobility capabilities and can move over virtually any type of terrain, including narrow and confined spaces. They are good climbers, very efficient swimmers, and some snakes can even fly by jumping off branches and using their body to glide through the air. Also, a snake robot is a highly articulated robot manipulator arm with the capability of providing its own propulsion.

In this work, we review recent results on modeling, analysis, and control of snake robots moving both on land and underwater. We also describe a new research direction within snake robotics, where underwater snake robots are equipped with thrusters along the body to improve maneuverability and provide hovering capabilities, and how this robot addresses current needs for subsea resident robots in the oil and gas industry.



**Contents**



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## 1. Introduction

The inspiration for snake robots comes from biological snakes. Snakes display excellent mobility capabilities and can move over virtually any type of terrain, including narrow and confined locations. They are good climbers, very efficient swimmers, and some snakes can even fly by jumping off branches and using their body to glide through the air. Also, a snake robot is a highly articulated robot manipulator arm with the capability of providing its own propulsion. These capabilities have spurred an extensive research activity investigating the design and control of snake robots.

A snake robot is a robotic mechanism designed to move like a biological snake. Inspired by the robustness and stability of the locomotion of biological snakes, snake robots carry the potential of meeting the growing need for robotic mobility in unknown and challenging environments. These mechanisms typically consist of many serially connected joint modules capable of bending in one or more planes. The many degrees of freedom of snake robots make them challenging to control, but provide potential locomotion skills in irregular and challenging environments which may surpass the mobility of wheeled, tracked and legged robots (Liljebäck, Pettersen, Stavdahl, & Gravdahl, 2012, 2013).

Research on snake robots has been conducted for several decades. The research field was pioneered about 40 years ago by Professor Shigeo Hirose at Tokyo Institute of Technology, who developed the world's first snake robot as early as 1972 (see Hirose, 1993). The robot, which is shown in Fig. 1, was equipped with passive wheels mounted tangentially along its body. The wheels enabled the robot to travel forward on a flat surface by controlling the joints according to a periodic body wave motion similar to the body waves displayed by biological snakes. In the decades following the pioneering research by Professor Hirose, research communities around the world have developed several agile and impressive snake robots in efforts to mimic the motion capabilities of their biological counterpart. In addition to the research of Shigeo Hirose's group, this includes the seminal works of the research groups of Howie Choset, e.g. Wright et al. (2007), Tesch et al. (2009), of Auke Ijspeert, e.g. Crespi, Badertscher, Guignard, and Ijspeert (2005); Crespi and Ijspeert (2008), of Gregory Chirikjian, e.g. Chirikjian and Burdick (1990, 1995), of Tetsuya Iwasaki, e.g. Prautsch, Mita, and Iwasaki (2000); Saito, Fukaya, and Iwasaki (2002), of Shugen Ma, e.g. Ma (1999, 2001), of Jim Ostrowski, e.g. Ostrowski and Burdick (1996); McIsaac and Ostrowski (2003), and of Fumitoshi Matsuno, e.g. Fukushima et al. (2012); Tanaka and Matsuno (2014). Please note that this list of significant researchers and papers on snake robots is by no means complete, and the reader is referred to the reviews of snake robotics research in Transeth, Pettersen, and Liljebäck (2008), Hirose and Yamada (2009), Hopkins, Spranklin, and S.K. (2009), Liljebäck, Pettersen, Stavdahl, and Gravdahl (2013), and Sanfilippo et al. (2017) for a more comprehensive exposition.

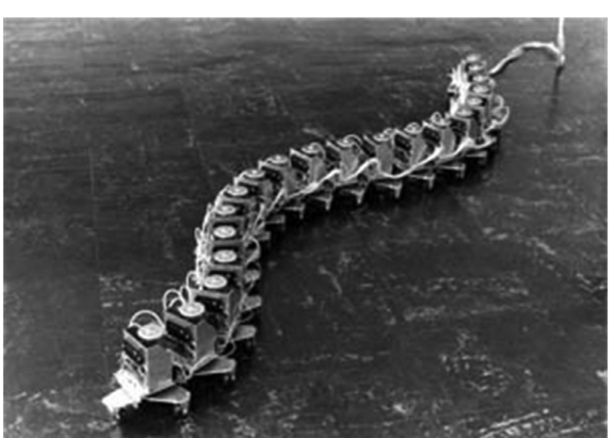

**Fig. 1.** The snake robot *ACM III*, which was the world's first snake robot developed by Prof. Shigeo Hirose in 1972. Courtesy of Tokyo Institute of Technology.

The present paper reviews a selection of recent work by the author's research group on modeling, analysis, and control of snake robots. A central goal of this work has been to understand the fundamental and inherent properties of snake robots, in order to efficiently control them. The primary focus of our research has thus been on model-based nonlinear analysis and control design. For experimental verification of the theoretical results, we have developed several dedicated snake robots, including Kulko (Fig. 2), a snake robot with force sensors, designed for obstacle-aided locomotion; Wheeko (Fig. 3), a snake robot with passive wheels, developed to study snake robot locomotion across flat surfaces; and Mamba (Fig. 4), an amphibious snake robot developed for experimental validation of modeling and control theory of swimming snake robots.

A first goal was thus to derive analytically tractable mathematical models of the snake robots and to utilize these to understand more about the properties of snake robots. The paper starts with a review of mathematical models of snake robots. The kinematics is similar regardless of whether the snake robot moves on land or in water, while the dynamics differs and is presented for snake robots moving on land in Section 2.3 and for snake robots moving underwater in Section 2.4. Then we move on the question of how to make the snake robot move forward. Based on the mathematical models, we see that if the friction or drag force coefficients of a snake robot are larger in the sideways direction than in the longitudinal direction of the robot links, the snake robot achieves forward propulsion by continuously changing its body shape to induce either ground friction forces or hydrodynamic drag forces that

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