WALKING-DIE : USING MEMS AND SOC FOR A MINIATURE ROBOT DESIGNED FOR NANOSCALE OPERATIONS

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Abstract

System-on-Chip (SoC) design methodology allows a high-level of integration in relatively complex electronic systems while Micro-Electro Mechanical Systems (MEMS) technology provides the ability to convert electric power to mechanical power with very small dimensions. These two technologies combined provide the opportunity to develop complex miniature robots. This paper introduces the Walking-die, an on-chip miniature robot of a few mm^2 designed for operations at the nanometer scale. Although several components are required to implement such a robot, this papers emphasizes on the custom parts of the systems used to embed most of the digital functions based on SoC technology and the locomotion system implemented using silicon MEMS.

Keywords: *MEMS, SoC, Nanotechnology, microfabrication.*

1. INTRODUCTION

The project Walking-die is an attempt to reduce the size of a previous robot capable of nanometer-scale operations called the NanoWalker [1]. The overall size of the later is in the order of 30 mm × 30 mm and it can be briefly described as a miniature autonomous robot for very high precision operations at the molecular scale via an embedded Scanning-Tunneling Microscope (STM) tip [2].

Once implemented, the Walking-die will have an overall size of a few millimeters. To achieve such a miniaturization, the high level of integration obtained with silicon Micro-Electro-Mechanical Systems (MEMS) and System-on-Chip (SoC) technologies [3] have been combined within the same system. The MEMS technology is used as a mechanical actuation generator mainly for the locomotion needs of the robot. The SoC technology is used to implement the embedded digital electronics at a higher level of integration.

By reducing the size, the overall performance in terms of relative displacement speed and operations executed per second is much lower than in the case of a larger instrumented robot such as the NanoWalker. Yet, we plan to compensate such loss by achieving higher parallelism through a larger number of Walking-die per surface area.

The Walking-die can be described as an electro-mechanical system with computation, communication, and instrumentation interface capabilities. The computation and communication capabilities are embedded onto a 0.18-micron CMOS processed die and two ICs, one being a 16-bit analog-to-digital converter (ADC) and the other an extremely low input bias current amplifier placed near the STM tip and configured as a tunneling current-to-voltage converter. The stacked electronic system will be mounted with a MEMS-based actuation system consisting of micromotors. The assembly will be realized on two non conductive glass slides: one per side of the robot. The dies will be connected by flat wire bonding on the same side of the slide and through the slides. The STM tip will be mounted between the two slides for a maximum balance of the system. In order to achieve a higher level of miniaturization, electrical power will be provided from the ground to the Walking-die using a special power floor.

The following sections introduce the SoC design methodology, the necessary SoC-based components embedded onto such a miniature robot to allow operations at the nanometer-scale and the MEMS micromotors [3] design methodology.

2. SYSTEM-ON-CHIP

The on board computer is embedded in a single die using SoC methodologies. The internal architecture of the system is made as simple as possible. As such, 16Kb of memory has been embedded to be used to program the robot [4]. For the communication system, in order to program the robot and to exchange data with a central computer, a one-wire bus was implemented, including a modulation and demodulation system [5]. Fig. 1 shows the block diagram architecture of the one-wire bus.

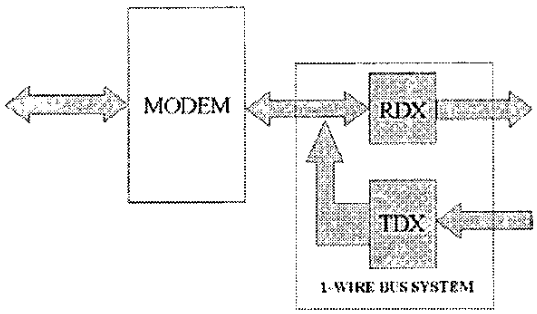

Fig. 1. One-wire bus system architecture

Fig. 2 shows the internal architecture of the robot. In other to reduce the complexity of the image some parts are not represented.

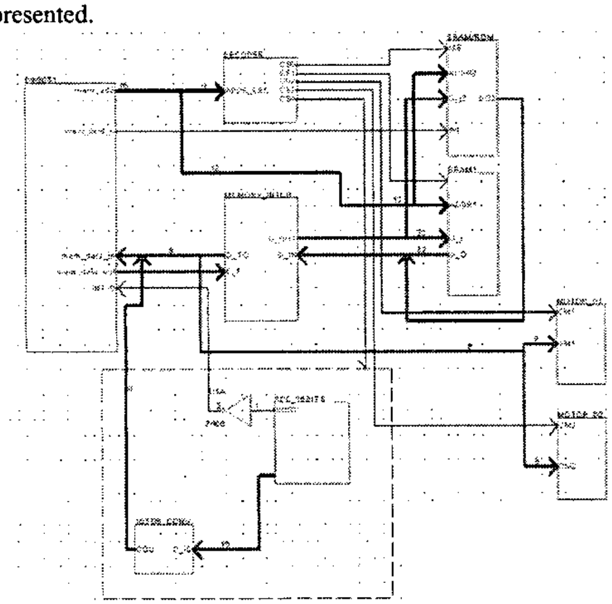

Fig. 2. Walking-die system architecture

The blue dot line in the Fig. 2 represents the logic necessary to control the A/D converter [6]. In other to avoid data contamination by analog components (electron migration) the ADC is wire bounded to the robot's main die containing the SoC. Two memory cores were implemented : one for program loading and the other for temporary data storage. A wrapper was implemented around these cores to interface the internal memories embedded onto a microcontroller. To control the MEMS actuators, two motor drivers have been implemented, one being assigned to each wheel.

3. MOTOR DRIVERS ARCHITECTURE

Two electrostatic motor drivers are designed to allow the robot to perform a variety of movements such as forward, backward and rotation. An internal three-wire bus is used to carry the commands specifying the type and speed of each movement. To facilitate the positioning task of the robot, the motor driver can work at three different speeds.

The MEMS technology allows us to build micro-motors which do not require analog signals. To produce forward and reverse rotation of the motor, as shown in Fig. 3, an aimed voltage pair of 6.6/0V is applied to each electrode at each opposite quadrants. In that picture, the black and gray regions represent the opposite quadrants.

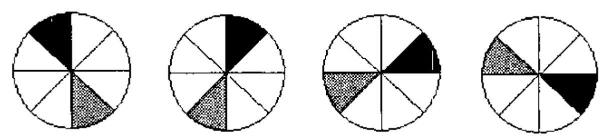

Fig. 3. Steps motor patterns

As depicted in Fig. 3, an 8 quadrants rotary side drive micromotor can provide up to three different rotation speeds while keeping a fluid motion.

4. CHOICE AND DESIGN OF ONE MICROMOTOR

Working at atomic scale requires uncompromised precision. In our case, the final step resolution of the robot must not exceed a few tenths of nanometers (nm). To simplify the design and decrease the level of embedded computation required for control, rotary elements were selected instead of more complex mechanisms such as a leg-based displacement [7] for instance.

Two main types of micromotors were initially considered: electrostatic [8, 9] and piezo-electric micromotors [10]. Electrostatic micromotors are faster but deliver less torque than the piezoelectric ones. The later would have been an obvious choice if the technology and assembly techniques did not put them out of the acceptable range in term of dimensions. The electrostatic micromotors can be built by microfabrication and reach a dimension of less than half a millimeter for the diameter of the rotor. The other dimensions are in the range of the thin layers techniques. Another advantage of using microfabrication is the easier integration of the electronic and mechanical parts which are then built

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with more compatibility due to the compatibility between CMOS and the microfabrication techniques.

The microfabrication of the micromotor was done using the MUMPS process. The design rules for such a process differ from the ones of a CMOS process mainly by the dimensions to be observed. MUMPS is a three polysilicon layers with an additional metallization layer process which uses 2 deposited oxide layers as sacrificial layers after Poly 0 and Poly 1, i.e. to structure Poly 1 and 2. An initial silicon nitride layer is deposited as an insulated and less stressed surface used to support the final structure.

The software proposed to design MEMS structure are mainly layout editors. Layout editors allow rapid and comprehensive mechanical design according to the process design rules. Some of them even offer a 3D visualization of the final structure according to the design rules of the process. The present design uses L-Edit from MEMsCap with its MEMS components library. This library greatly helped in designing the rotary side drive micromotor in much less time by offering pre-designed basic mechanical elements i.e. pre-aligned masks.

Decision was made to design oversized rotor poles to have 2 stator electrodes for 1 rotor pole as shown in Fig 4.

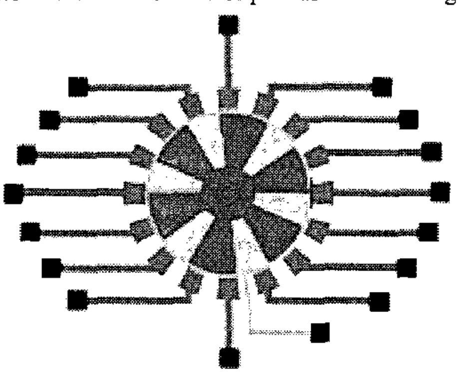

Fig. 4. Drawing of the mask of the micromotor

The design depicted in Fig. 4 can potentially give the possibility to obtain more torque while slowing down the rotation speed and making it smoother. Consequently, the rotor ring was made slightly oversized to preserve the integrity of the structure and strategically put small holes one the rotor surface to reduce its weight. Some dimples support this Poly rotor over another Poly layer. The stator electrodes, also mainly made of Poly, slightly go over the rotor layer as depicted in Fig. 5.

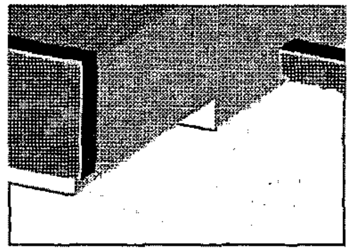

Fig.5. Stator electrode prolongation

The conductivity of those layers is the key to the electrostatic displacement of the rotor. An electrical current is applied to the structure in a manner to produce a potential difference between the electrodes and the Poly layer underneath the rotor. The resulting attraction field is then used to drive the rotor which is in physical contact with its support Poly layer by its dimples.

The bearing is a simple mushroom cap structure attached to the Poly layer under the rotor. The initial rotation ratio of 1:1 could eventually be changed by using microfabricated mechanical gears and modifying the actual design.

The Walking-die will reach an estimated weight of less than a gram and we expect the micromotors to give us some base mechanical power in the order of 10^{-4} N.

Other factors such as friction and ambient pressure problems have also to be taken into account in the design. In fact, to those we must add humidity, stiction and others issues inherent to the fabrication process. Like in the case of the CMOS processes, only a certain number of designs survive the fabrication stage. To maximize our chances of success, we initially favored for a more conservative design approach.

5. SUMMARY

This paper introduced the design methodologies and integration of SoC and MEMS components for a miniature robot designed for nanoscale operations, named Walking-die.

While the SoC methodology provided a mean to embed computation and most of the digital electronic functions needed, the MEMS technology was used as a main source of mechanical power and to provide the necessary control over the precision and speed of displacement of the robot.

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