Achieving increased functionality and efficiency in vacuum robots

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Introduction

Vacuum robots continue to experience greater acceptance and use as augmentation, and even replacement, of manual vacuum cleaners in residences and commercial enterprises. To be able to perform in complex and even cluttered environments, these robots must be able to process a great deal of sensing data about their environment and operate within a prescribed mapping protocol that enables them to effectively and efficiently clean the desired target regions, all while avoiding operationally fatal scenarios. Newer trends in vacuum robots such as integration of wireless connectivity to the cloud, advanced sensor integration to cover diverse environments and voice recognition enabling home automation are making them smarter and more efficient.

Rapidly developing technologies and system solutions provided by companies such as Texas Instruments (TI) will provide more options for consumers seeking a vacuum robot that meet their specific needs and environmental constraints.

Differentiation among vacuum robots

You can generally differentiate vacuum robots by their navigation strategy, the effectiveness of the cleaning device, and the ease of interaction with consumers, such as the human-machine interface (HMI) employed to start, stop and schedule the cleaning process.

Regarding mapping and navigation, three general approaches are used, and some vacuum robots use more than one of them. These approaches are:

- Following a random walk using predefined behaviors (wall following, spirals and obstacle avoidance).
- Performing ceiling visual-simultaneous localization and mapping (CV-SLAM) using a ceiling vision system that consists of a single camera pointing upward.
- Using a low-cost laser-range scanner for 2-D laser SLAM.

A vacuum robot's cleaning effectiveness tends to be a function of the "roughness" of the surface areas it cleans, the effectiveness of the agitator and other brushes, and its suction power.

A useful HMI enables the easy programming of cleaning schedules; manual start and stop; cleaning time estimation per room; and, during the cleaning process, determining what has already been cleaned and/or what remains to be cleaned, along with the time required to complete this.

Vacuum robot functional/operational requirements and challenges

Several critical factors and requirements are more or less common to all vacuum robots pertaining to power and operation.

Since this is a portable application, battery efficiency is important. Cleaning performance (agitator, dirt sensors and suction power) and environmental sensing and mapping requirements place challenging demands on the battery. As a result, you must consider all of these subsystems and related operational factors in your battery design. Considerations include factors such as the size and weight of the battery itself. A larger-sized rechargeable nickel-metal hydride (NiMH) battery will extend operational time but will also add weight and place an additional load on the frame, wheels and wheel motors. You must balance these factors in order to arrive at an optimal runtime between charges.

A typical battery pack is rated at 3 Ah. When fully charged, an 18-V battery will provide around two hours of cleaning time (three medium-sized rooms) before needing to recharge. Earlier-generation vacuum robots required up to seven hours to fully charge the battery, while newer units can fully charge in two hours or less.

The number of motors, including their efficiency and motor switching, is an important factor as well. A typical vacuum robot may contain as many as five (or more) motors:

- One motor driving each wheel (two total).
- One driving the vacuum.
- One driving a spinning side brush, if present.
- One driving the agitator assembly.

As a result, both effective mapping (discussed below) and efficient motor-control processing are critical in order to minimize extraneous braking and redundant travel.

Fast charging is also critical, since cleaning more than three rooms will require one or more returns to the base unit for charging, adding nontrivial time to the overall operation.

The final element of the power vs. runtime equation is the effectiveness of the mapping operation and return-to-base operation. Consumers expect their robots to clean each room with 100% coverage, but this is not possible if there are redundant and inefficient coverage algorithms.

A number of environmental factors impact effective cleaning, including the density of furniture and other objects present as well as the variety of surface areas—along with the commensurate smooth floor-to-carpet transitions. An excessive density of objects will cause the vacuum robot to invoke its object-avoidance mechanism excessively, while a higher carpet-to-floor-area ratio will put greater strain on the actuator and vacuum motors, thereby reducing the duration of cleaning time between charges. Dirt, spills and other high concentrations of debris require additional attention above the standard cleaning process and associated travel paths.

Finally, the avoidance of an operationally fatal event like falling down stairs, off of balconies or off of "step-downs," must be incorporated into to the vacuum robot design, to ensure that the cleaning process is not interrupted or aborted. Also included in the avoidance category are low-height "wedge" environments within which the vacuum robot could become caught. Further, wet or flooded environments could disable the cleaning mechanism or electrically damage the unit.

Technical requirements for vacuum robots

Vacuum robot manufacturers must balance the desire for power-efficient operation against the cleaning effectiveness that consumers demand. Achieving these often mutually exclusive goals is the result of trading off the requirements of the many interdependent subsystems within a vacuum robot.

Since many vacuum robot cleaning tasks encompass multiple rooms and exceed the available power of the battery's capacity, and since the robot must recharge its battery between cleanings, the unit must be able to determine when a recharge is required and ensure that sufficient charge remains to communicate with and power the wheel motors back to the charging unit. The unit must either "remember" its way back to the base, or it will need to be able to communicate with the unit to find it. Receiving commands from an infrared (IR) remote control or a consumer's smartphone, typically through the Internet/Wi-Fi®, requires additional communication capabilities.

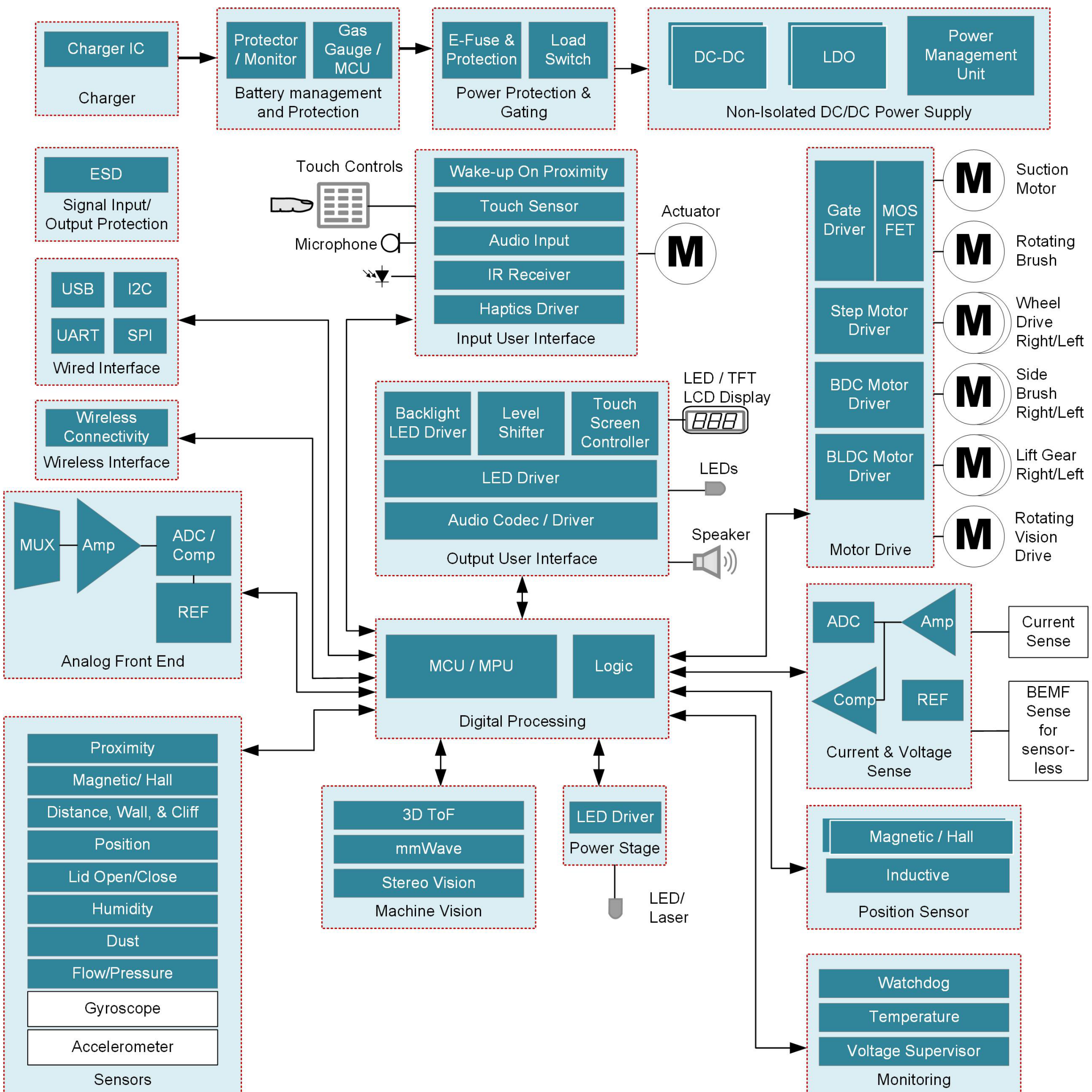

Figure 1: TI vacuum robot reference diagram.

The integration of IR and camera-sensing and mapping information, robot decision-making regarding perimeter and coverage mapping, and obstacle and risk ("cliff") avoidance increases the logic programming requirements. One manufacturer claims that one of its vacuum robots can adapt to a new input 67 times per second.

To address areas that contain an excessive amount of dirt or debris, some vacuum robots employ "dirt sensors," which are acoustic impact sensors that register vibrations associated with dirt and debris colliding with the metal plates of the sensors. The processor interprets this occurrence as one representing a high-dirt area and modifies the cleaning map and time spent canvassing the area accordingly.

Considering the multitude of real-time sensor data and operational feedback, a vacuum robot must quickly process a nontrivial amount of data and respond in the most effective manner. This in turn puts demands on the processor serving as the "brain." Correspondingly, as designers add new technologies that increase efficiency and functionality, the ease of programming such new features into the control system software platform becomes essential.

Finally, the robot itself requires a small form factor in order to access remote and low-clearance areas. A small size and weight will enable the robot to operate for longer periods before needing to recharge.

TI enabling technologies for vacuum robots

TI offers a full range of advanced technologies that enable the design of flexible and operationally efficient vacuum robots that can operate within the complex physical constraints of most residences and commercial enterprises. From sensor input to actuator or motor output, TI solutions handle the entire signal chain while also providing the processor power for vacuum robot operation. These solutions include:

- **Sitara™ processors**. The heart of any vacuum robot control unit is the processor. The processor interfaces with various sensors, aggregates and processes data and makes intelligent navigation decisions by driving the motors. Additional functions of the processor include connectivity, HMI and voice recognition. TI's system-optimized Sitara processors are designed for flexible, fast design in vacuum robot applications. Based on Arm® Cortex®-A cores, Sitara processors incorporate a variety of flexible peripherals, connectivity and unified software support to cover a wide set of vacuum robot operational requirements and applications. A broad portfolio of single- and multicore devices provides a selection of processor options that offers the optimal balance of integration, connectivity and performance for every vacuum robot application and subsystem. Furthermore, a fully scalable software platform enables a unified software experience for simplified development and code migration across all Sitara processors and TI digital signal processor (DSP) families. Pin-compatible options within some of these processor families make hardware upgrades virtually seamless. See Table 1 on the following page.

  Built-in hardware acceleration (cryptographic, 2-D/3-D graphics and video), native ICSS protocol support for more commercial applications and extensive software libraries from TI and third parties dramatically reduce time to market.

  TI's Processor SDK, which provides a common user interface and software platform for all

	AM335x processor	AM437x processor	AM57x processor
Core	Arm Cortex-A8 up to 1 GHz	Arm Cortex-A9 up to 1 GHz	1 or 2 Arm Cortex-A15s up to 1.5 GHz 1 or 2 C66x DSPs up to 750 MHz
Dhrystone million instructions per second (DMIPS) (max)	2,000	2,500	10,500
Multimedia	SGX530	SGX530	1 or 2 SGX544 3-Ds, GC320 2-D, high-definition imaging and video accelerator (IVA-HD)
Coprocessors	Dual-core programmable real-time unit subsystem and industrial communication subsystem (PRU-ICSS)	Quad-core PRU-ICSS	Quad-core PRU-ICSS, dual-core Arm Cortex-M4
Memory	Low-power (LP) double-data rate (DDR) 1/DDR2/DDR3(L)	LPDDR2/DDR3(L)	1 or 2 32-bit DDR3(L)
OS	Linux®, Android™, TI-real-time operating system (RTOS)	Linux, TI-RTOS	Linux, TI-RTOS, Android
Key features	Liquid crystal display (LCD) controller, Controller Area Network (CAN), gigabit Ethernet Media Access Controller (EMAC) switch, 2 USB with physical layer (PHY), Enhanced high-resolution PWM	Display subsystem, dual camera, Quad Serial Peripheral Interface (QSPI), gigabit EMAC switch, 2 USB with PHY, Enhanced high-resolution PWM	Display subsystem, USB 3.0, Serial Advanced Technology Attachment (SATA), Peripheral Component Interconnect Express (PCIe), video inputs, High-Definition Multimedia Interface (HDMI), 3 LCD outputs, Enhanced high-resolution PWM

Table 1. *Sitara processor family features.*

Sitara devices, greatly leverages engineering resource investments across multiple Sitara Arm-based processor families. Furthermore, where depth cameras are required, TI's Processor SDK also incorporates a voxel software development kit (SDK) as one of many built-in software components, thereby reducing the number of diverse software modules requiring integration.

The variety of general-purpose and industrial evaluation modules (EVMs)—combined with Processor SDK bring-up, application and feature-demonstration software—contribute to a productive out-of-box experience.

By enabling seamless development on (and across) multiple Sitara and even DSP product lines, you have unencumbered options in your choice of TI processor device(s). You can choose solutions based on:

- Peripherals:
  - SPI
  - Multichannel SPI (McSPI)
  - Camera Serial Interface (CSI)
  - USB 2.0/3.0
  - CAN
  - Multichannel Audio Serial Port (McASP)
  - Gigabit Ethernet switching
  - PCIe
  - SATA
- Core speed:
  - 300MHz to 1.5GHz
- Core technology:
  - Arm Cortex-A8
  - Arm Cortex-A9
  - Arm Cortex-A15
  - C66x DSP

Within each family of Sitara processors, you can achieve further cost savings by reducing the number of unnecessary features or cores, all within common pin-compatible packages.

Sitara processors are designed to meet industrial requirements for long-term applications, with extended-temperature-range options, enabling use in both residential and commercial enterprises.

- **Proximity sensing.** More sophisticated sensing and mapping operations are enabling vacuum robots with improved performance and efficiency. TI sensing technology solutions for proximity sensing can detect the presence of objects in an environment and measure its distance if required. Techniques that TI supports for proximity sensing include ultrasonic, magnetic capacitance, inductive and time of flight (ToF).
- **3-D ToF/optical sensing.** TI products enable ToF-based sensing to go beyond proximity detection to next-generation machine vision. Improving vacuum robot vision via 3-D ToF technology enables the robot to accurately detect and recognize objects at a distance, as well as being able to map their environment. The establishment of optimal vacuuming paths optimizes both surface coverage and vacuuming times, while also avoiding collisions, falls and wedge environments.

  TI's 3-D ToF chipsets enable maximum flexibility to customize designs for robot vision and other applications. TI tools related to 3-D ToF include an EVM and a highly configurable camera development kit (CDK); the latter provides 3-D locations of each pixel for accurate depth and distance maps that aid customization for efficient vacuum robot "terrain" coverage.
- **Connectivity solutions**. TI offers solutions for integrating communication capabilities for its processors. The TI WiLink™ 8 combo connectivity module family enables developers to easily add fully integrated 2.4- and 5-GHz versions of Wi-Fi and dual-mode *Bluetooth*® 4.0 solutions to embedded applications. WiLink 8 modules are a good fit for power-optimized vacuum robot applications. WiLink 8 modules and software are both compatible and pre-integrated with a wide range of processors, including TI's Sitara processor family. Used together, designers have access to a high-performance platform enabling cloud connectivity, high wireless throughput, integrated dual-mode Bluetooth and Wi-Fi connectivity, and a unified programming experience to control the system. TI Sitara processors also integrate security features including secure boot and runtime security, which are useful to enable secure connectivity.
- **Voice recognition.** TI Sitara processors offer voice recognition with integrated DSPs. The DSPs offer excellent voice processing capabilities to extract clear speech and audio amidst noise and other clutter.
- **Efficient power-supply solutions.** TI offers a wide variety of power-management integrated circuit (PMIC) solutions for various devices, including low-power options (Table 2 lists several) for vacuum robot and other mobile and portable applications.

	Device	PMIC
 Sitara (AMxxxx)	AM335x	TPS65910, TPS65217, TPS650250, TPS65218
	AM437x, AM438x	TPS65218
	AM572x	TPS659037x
	AM571x	TPS659037x, TPS65916
	AM570x	LP8733, LP8732, TPS65916

Table 2. *Power solutions for Sitara devices.*

Building better, more efficient vacuum robots for residences and commercial enterprises

As technology advances and continues to expand the performance and efficiencies of vacuum robots, their presence and ubiquity in residences and commercial enterprises will expand as well. The increased capability demands fueling this growth will compel vacuum robot developers to look for solutions that will enable them to deliver accurate, efficient, safe and cost-effective operation for their products.

TI's IC products for sensing, signaling, processing, communications and power management provide the complete solutions that vacuum robot developers require and demand. TI supports its semiconductor and IC products with software tools, EVMs, reference designs and other avenues of support that help speed time to market, thus making the process of designing and delivering vacuum robots more responsive, timely and profitable.

As vacuum robots are improving the quality of life for consumers and businesses, TI is helping the developers of these products continually improve them and enhance their effectiveness.