Mimicking the Sense of Smell of Search and Rescue (SAR) Dogs: a Bio-inspired Steering Framework for Quadruped Robots

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ABSTRACT

Due to their sense of smell and ability to explore areas for missing people, dogs are valuable for search and rescue (SAR). Canines can discover humans under water, under snow, and even beneath crumbling structures because they can smell human scent. Building unmanned autonomous quadruped robots with canine agility is an attractive step to fully replicate the capabilities of dogs. Robots with legs are already capable of mimicking some of the physical traits of dogs, such as the capacity to traverse rough terrain. However, they would need to replicate also the level of sensory perception of a dog to successfully perform SAR operations. To achieve this, a navigation strategy that uses a direct sensor-motor coupling by following the principles of the Braitenberg vehicles is adopted in this work. This paper represents one of the first steps towards the connection of bio-inspired sensor-based steering mechanisms and bio-inspired locomotion for quadruped robots.

Keywords

Quadruped Robots, Search and Rescue (SAR), Dogs, Perception.

INTRODUCTION

One of the main strengths of rescue dogs is their olfactory system, which is highly developed and allows them to detect and track scents over long distances. This ability is remarkably useful in search and rescue (SAR) operations, where they can use their sense of smell to locate humans who are lost or trapped (Bauer 2011). Rescue dogs are also highly agile and capable of navigating a wide range of terrains, including uneven and cluttered surfaces. This allows them to access areas that may be difficult or impossible for humans to reach. Nonetheless, rescue dogs also have some restraints. They are living, breathing animals, and they require food, water, shelter, and medical care. This can make them more difficult to deploy in certain scenarios, such as in remote or hostile environments. Additionally, rescue dogs may be limited by their physical abilities, such as their strength, speed and endurance. Because of this, they could perform worse in circumstances where time is of the essence.

One of the most appealing ways to fully emulate the capabilities of biological dogs is to create unmanned autonomous quadruped robots that can match canine characteristics while minimising their limitations. Arguably, the main strength of quadruped robots is their ability to operate in a wide range of environments, including those that are hostile or inhospitable to humans or canines (Bellicoso et al. 2018). Quadruped robots are not affected by temperature, weather, or terrain, and they do not require food, water, shelter, or medical care. This makes them well-suited for use in remote or hazardous environments, where they can operate for extended periods of time without the need for support. However, quadruped robots lack a sense of smell, as they do not have the same

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Figure 1. The concept of replicating canine search and rescue (SAR) capabilities with bio-inspired quadruped robots. Elements of this figure are courtesy of the National Disaster Search Dog Foundation

biological structures and processes as canines. Instead, they frequently have sensors (Wermelinger et al. 2016; Tadokoro 2019; Marques 2020) and other technology (e.g., RGB-D terrain perception and dense mapping (Belter et al. 2016), or acoustics based terrain classification (Christie and Kottege 2016)) that let them perceive their surroundings in a variety of ways. Some quadruped robots may be equipped with sensors that can detect specific chemicals or gases, but these sensors are not as sensitive or versatile as the canine olfactory system. Therefore, quadruped robots are not yet as effective as canines when it comes to tasks that require a keen sense of smell.

To enable quadruped robots with the possibility of resembling a comparable degree of sensory perception as canines in successfully performing SAR operations, the applicability of reactive navigation techniques based on an instantaneously measured spatial gradient is presented in this paper. Specifically, a localisation strategy that uses a direct sensor-motor coupling by following the principles of the Braitenberg vehicles (Braitenberg 1986) is employed. Braitenberg vehicles are typically designed to resemble the behaviour of simple animals, such as insects or mammals and have been used in pioneering works on chemical sensing based navigation (Lilienthal and Duckett 2003) . A Braitenberg vehicle, for instance, might be configured to move in a straight line, avoid obstacles, or follow a light source, based on a stimulus (Ranó 2012). Although the majority of the existing Braitenberg vehicle implementations are based on wheeled robots, the qualitative principles for the design of these steering level controllers can be extended to other types of locomotive mechanisms (Ranó et al. 2018; Salumäe et al. 2012). This, therefore, opens up the question of how to adapt these principles to locomotive systems other than active wheels, i.e., how to connect the steering and the locomotive systems for these bio-inspired steering controllers. This paper represents a pioneering effort toward bridging the existing gap in the connection between bio-inspired steering and locomotion. Using the principles of Braitenberg vehicles this work implements a positive taxis (as in the movement of an organism) behaviour in a simulated quadruped robot, and demonstrates that the resulting trajectory of the robot matches the theoretical results obtained for wheeled vehicles with active wheels. In this paper olfaction is replaced by light perception as accurately simulating odour is extremely challenging. The underlying concept is depicted in figure 1.

This paper is organised as follows. A review of the related research works is given successively. Then, a cost comparison about training a SAR dog versus developing a quadruped robot is discussed. A Braitenberg vehicle model of a quadruped robot is later provided. Subsequently, simulations are presented, which show how the proposed taxis approach works for our simulated legged locomotion mechanism. Finally, conclusions and future works are discussed.

RELATED RESEARCH WORKS

Recent research and development has focused on the development of quadruped robots that can imitate the capabilities of dogs. The ability of these robots to quickly and effectively search vast regions for missing individuals makes them potentially useful instruments in SAR missions yet, these robots must be able to imitate canine physical characteristics, such as their capacity for fast movement across uneven ground. A survey that concentrates on various design and development approaches for quadrupedal robots is presented in (Biswal and Mohanty 2021). To help quadruped robots imitate the capabilities of dogs, several steps are necessary, such as; understanding the specific capabilities of canines, designing the robot's body and developing movement systems to match these capabilities (Zhong et al. 2019). Another crucial step consists of implementing sensors and control systems that allow the robot to perceive and navigate its environment in a similar way to dogs. A sensory perception system can include a range of sensors, such as cameras, lidar, and other sensors. This system can also include algorithms that help the robot to interpret the data they gather from its sensors and make decisions about how to move and act in order to accomplish its objectives. Some of these algorithms could aim at mimicking the sense of smell of dogs. In fact, dogs have an incredible sense of smell that allows them to detect a wide range of odours, including those that are too faint for humans to perceive. This ability is particularly useful in SAR operations, where dogs are often used to locate missing persons or identify the presence of hazardous materials. By incorporating a sense of smell into the sensory perception system of robots, quadruped robots could potentially detect odours that would otherwise go unnoticed, allowing them to more effectively navigate and search their environment. Additionally, the ability to detect and differentiate between various odours could potentially provide robots with valuable information about their surroundings, such as the presence of people or objects, or even changes in the environment over time. Overall, mimicking the sense of smell of dogs could greatly enhance the perception abilities of robots, making them more effective in a wide range of applications. In this respect, Braitenberg vehicles (Braitenberg 1986) could be used to mimic the sense of smell of dogs (Lilienthal and Duckett 2003), as these algorithms are designed to control the behaviour of robots in response to sensory inputs. However, the literature is rather thin on works on this subject. Regarding other kind of stimuli, such as sound, a preliminary Braitenberg vehicle–like approach was presented in (Shaikh et al. 2011) to combine bio-inspired audition with bio-inspired quadruped locomotion in simulation. Locomotion gaits of the salamander–like robot Salamandra robotica are modified by a lizard's peripheral auditory system model that modulates the parameters of the locomotor central pattern generators. Even though this work shows the potential of Braitenberg vehicles, this study still represents a preliminary approach. To the best of our knowledge, a bio-inspired steering framework for quadruped robots is still missing.

TRAINING A SAR DOG VS. DEVELOPING A QUADRUPED ROBOT

While the development of autonomous quadruped robots for SAR missions shows great potential, it is critical to recognise the cost disparities between training a dog and building a robot. Depending on the degree of training necessary and the unique abilities the dog will be charged with, the cost of training a SAR dog can range from several thousand dollars to tens of thousands of dollars. This covers training, feeding, and care fees, as well as any required equipment and supplies. The expense of constructing a quadruped robot for SAR operations, on the other hand, is substantially greater, with estimates ranging from hundreds of thousands to millions of dollars. This is owing to the significant science and engineering necessary to construct a robot capable of mimicking a dog's physical capabilities and sensory awareness. Furthermore, regular maintenance and improvements will increase the cost of running a robot. While the potential benefits of deploying robots for SAR operations are enormous, the cost and resources necessary to build these robots, as well as the continuous expenses of operation and maintenance, must be considered. Dogs will likely continue to be the primary approach for SAR operations until the expense of designing and operating a robot is comparable to the cost of training a dog.

In addition to the technological and financial hurdles of building robot dogs for SAR missions, various ethical issues must be addressed (Chitikena et al. 2023). The employment of robots in SAR operations raises concerns about the accountability and responsibility of the robots and their operators, as well as the possible harm that robots may bring to both victims and rescuers. Concerns have also been raised concerning the privacy and security of sensitive information obtained by robots during SAR operations, as well as the possibility of robots being hacked or used maliciously. Furthermore, it is critical to guarantee that the use of robots in SAR operations does not remove or weaken the role of human rescuers and their vital contributions. It is also crucial to address the psychological impact of being rescued by robots on victims and their relatives, as well as the possible emotional impact on human rescuers if they are replaced by robots in SAR operations. Addressing these ethical issues is critical to assuring the appropriate and effective deployment of robot dogs in SAR missions, as well as public confidence and acceptance of this technology.

Another major consideration in the development of robot dogs for SAR operations is the creation of user-friendly interfaces for commanding the robots. In an emergency, time is of the essence, and first responders must be able to rapidly and efficiently manage the robots to accomplish their essential duties. First responders can successfully manage the robots and carry out SAR operations more efficiently and effectively by building simple and user-friendly interfaces (i.e., with a multi-modal auditory-visual-tactile approach (Sanfilippo, Blažauskas, et al. 2022), or with the use of virtual reality/augmented reality (VR/AR) (Sanfilippo, Blazauskas, et al. 2022)). Furthermore, by making it easy for first responders to manage the robots, they will be more inclined to trust and accept this technology, improving the likelihood of SAR mission success. The creation of user-friendly interfaces will be critical to the successful deployment of robot dogs for SAR missions, as well as ensuring that the technology is utilised successfully and ethically.

Another key consideration in the development of robot dogs for SAR operations is the use of soft actuators (Tuan et al. 2021; Tuan et al. 2022) to make human-robot interaction safer. Soft actuators constructed of flexible materials, for example, can assist to reduce the danger of damage to both victims and rescuers during SAR operations. It

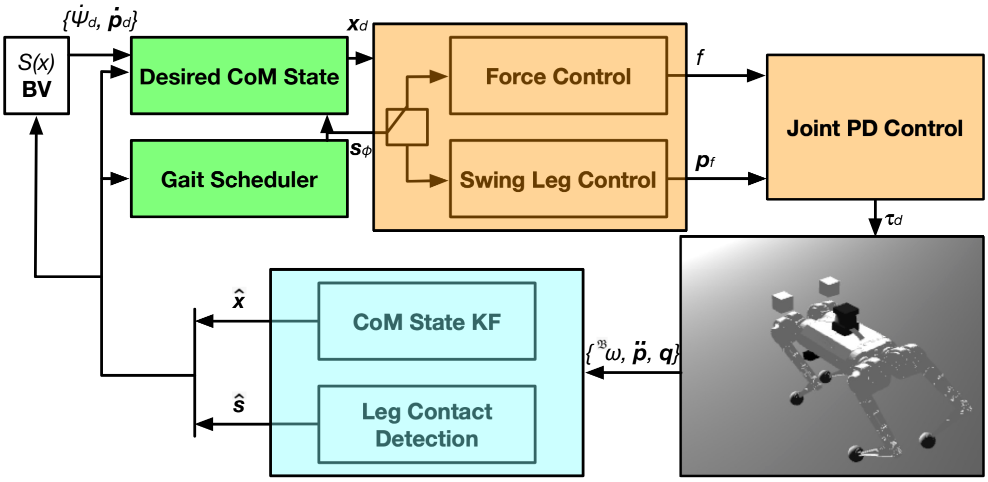

Figure 2. The control architecture for the Braitenberg quadruped robot. The following abbreviations are used: center of mass (CoM), proportional derivative (PD), Kalman filter (KF).

will be feasible to lessen the danger of harm during interactions with people by introducing soft actuators into the design of robot dogs, making the technology safer for everyone involved. This is especially crucial in SAR efforts, because victims may be weaker or injured and therefore more vulnerable to damage. Soft actuators will assist to limit the potential of future harm while also ensuring that robots are utilised properly and ethically in SAR operations. The use of soft actuators will be important in the development of robot dogs for SAR missions, ensuring that the technology is employed safely and effectively.

It is worth noting that the utilisation of robot teams comprised of heterogeneous robots, i.e., legged robots, snake robots (Sanfilippo, Helgerud, et al. 2019; Duivon et al. 2022), grasping robots (Sanfilippo 2022), aquatic robots (Sanfilippo, Tang, et al. 2021), humanoid robots (Sanfilippo, Smith, et al. 2022) and aerial robots will allow for a more effective response in SAR missions. It will be feasible to give a more complete and effective response to emergencies by integrating the specific characteristics of each type of robot. Legged robots, for example, can traverse uneven terrain and travel through difficult surroundings, snake robots can enter tiny places and difficult-to-reach regions, and aerial robots may give a bird's eye perspective of the disaster zone and do aerial reconnaissance. By integrating these capabilities, it will be possible to respond to emergencies in a more effective and efficient manner, ensuring the safety of both victims and rescuers. In conclusion, the development of heterogeneous robot dogs for SAR operations is an exciting step forward in robotics, and the employment of robot teams will allow for a more comprehensive and effective response to crises.

Furthermore, developments in indoor (Ho-Sy et al. 2019) and harsh environment navigation algorithms will lead to the usage of robots for SAR missions. In catastrophe circumstances, it is important to navigate through complicated and unexpected settings, such as damaged or collapsed buildings. The development of improved navigation algorithms will allow robot dogs to more efficiently explore these situations and carry out SAR missions. Algorithms that allow robots to map and explore unfamiliar surroundings, cope with obstacles (Sanfilippo, Azpiazu, et al. 2017; Sanfilippo, Stavdahl, et al. 2018), and design safe and efficient courses, for example, will be important for the effective deployment of robots for SAR missions.

A BRAITENBERG VEHICLE MODEL OF A QUADRUPED ROBOT

This section presents the adopted model of the quadruped robot and the control architecture, which is shown in figure 2. First, the model of the quadruped robot dynamics is outlined. Then, a description is presented regarding how the robot is controlled by a joint-level proportional derivative (PD) controller to track the movement gait signal. The control architecture is composed of three main parts: higher-level planning (green), leg and body control (red), and state estimation (blue). The robot receives force and position commands for each leg, which are then used to generate the corresponding motor commands. The parameters of the gait generator are modulated through the implementation of a Braitenberg vehicle 3a using the sensors placed on the robot head. Regarding the outer controller, the Braitenberg vehicle (BV) block, receives the pose of the quadruped robot (estimated state $\hat{s}$, position and orientation, $\hat{x}$) as an input, evaluates a stimulus function $S(x)$ at the points of where the sensors are located and outputs the parameters for the gait generator (i.e., desired translational velocity, $\dot{\mathbf{p}}_d$, and turning rate, $\dot{\psi}_d$). These signals are adapted to plan a smooth and controllable center of mass (CoM) reference trajectory that is relayed to the body and leg controllers. Various controllers and planners use the BV outputs and the estimated robot state to generate force commands if the leg is in stance or position commands if the leg is in the swing stage.

Dynamic modelling of the quadruped robot

In this work, the model of a robust, dynamic quadruped robot, namely the Massachusetts Institute of Technology (MIT) Cheetah 3 is considered (Bledt et al. 2018). The modelling of this robot is briefly summarised in this section. For further details, the reader is referred to (Bledt et al. 2018).

Gait generation and independent joint position control

The way the Cheetah moves is determined by a system that uses an event-based finite state machine and a leg-independent phase variable to plan when each leg should be in contact with the ground and when it should be swinging. This system allows for a range of different movement patterns, including trotting, bounding, and pacing, and makes it easy to add new patterns. These gaits were created to imitate the way real cheetahs move by controlling the individual phases of each leg. When unexpected contact events on the legs occur, this nominal gait plan is altered. Scheduled contacts are defined by independent boolean variables $s_\phi \in \{0 = swing, 1 = contact\}$, while estimated contacts are given by $\hat{s} \in \{0 = swing, 1 = contact\}$. With the use of this data, the robot can distinguish between normal operation, unexpected early contacts, and late missed contacts, and then modify its control actions accordingly.

Control model

It is challenging to use traditional control methods to balance robots with hybrid movements that involve switching between different modes of leg movement. The controllers used on the robot in this case use simplified control models to optimise ground reaction forces at the footstep locations. The robot has lightweight limbs with low inertia compared to its body, which allows the control model to ignore the effects of the legs for planning ground reaction forces from the stance feet. The Cheetah 3 controller model uses a common linear relationship (Focchi et al. 2017) between the robot's CoM translational $\ddot{\mathbf{p}}_c$ and body angular acceleration $\dot{\omega}_b$ and the forces $\mathbf{F} = (\mathbf{F}_1^T, \mathbf{F}_2^T, \mathbf{F}_3^T, \mathbf{F}_4^T)^T$ acting on each of the robot's four feet. The controller model is given by:

$$\underbrace{\begin{bmatrix} \mathbf{I}_3 & \dots & \mathbf{I}_3 \\ [\mathbf{p}_1 - \mathbf{p}_c]\times & \dots & [\mathbf{p}_4 - \mathbf{p}_c]\times \end{bmatrix}}_{\mathbf{A}} \mathbf{F} = \underbrace{\begin{bmatrix} m(\ddot{\mathbf{p}}_c + \mathbf{g}) \\ \mathbf{I}_G \dot{\omega}_b \end{bmatrix}}_{\mathbf{b}} \tag{1}$$

where m and $\mathbf{I}_G$ are the robot's total mass and centroidal rotational inertia, $\mathbf{g}$ is the gravity vector and $\mathbf{p}_i, i \in \{1, 2, 3, 4\}$ are the positions of the feet. The term $[\mathbf{p}_i - \mathbf{p}_c]\times$ is the skew-symmetric matrix representing the cross product $[\mathbf{p}_i - \mathbf{p}_c] \times \mathbf{F}_i$.

Force Control - Balance Controller

One of the Cheetah 3 support leg control modes is a Balance Controller, which is an implementation (with slight modification) of the controller described in (Focchi et al. 2017). The Balance Controller enforces PD control on the center of mass and body orientation, while also making sure that foot forces satisfy friction constraints. The PD control law is given by:

$$\begin{bmatrix} \ddot{\mathbf{p}}_{c,d} \\ \dot{\omega}_{b,d} \end{bmatrix} = \begin{bmatrix} \mathbf{K}_{p,p}(\mathbf{p}_{c,d} - \mathbf{p}_c) + \mathbf{K}_{d,p}(\dot{\mathbf{p}}_{c,d} - \dot{\mathbf{p}}_c) \\ \mathbf{K}_{p,\omega} \log(\mathbf{R}_d \mathbf{R}^T) + \mathbf{K}_{d,\omega}(\omega_{b,d} - \omega) \end{bmatrix} \tag{2}$$

The desired angular acceleration reflects PD control on SO(3) wherein the desired and actual body orientations are described using rotation matrices $\mathbf{R}_d$ and $\mathbf{R}$, respectively, and the orientation error is obtained using the exponential map representation of rotations (Bullo and Murray 1995; Murray et al. 2017).

The Balance Controller's objective is to resolve an optimal distribution of leg forces F that drive the approximate CoM dynamics to the corresponding desired dynamics given by:

$$\mathbf{b}_d = \begin{bmatrix} m(\ddot{\boldsymbol{p}}_{c,d} + \boldsymbol{g}) \\ \mathbf{I}_G \dot{\omega}_{b,d} \end{bmatrix} \tag{3}$$

Since the model (1) is linear, the controller can naturally be expressed as the solution of a quadratic program (QP) (Gehring et al. 2013):

$$\mathbf{F}^* = \min_{\mathbf{F} \in \mathbb{R}^{12}} (\mathbf{AF} - \mathbf{b}_d)^T \mathbf{S} (\mathbf{AF} - \mathbf{b}_d) + \alpha \|\mathbf{F}\|^2 + \beta \|\mathbf{F} - \mathbf{F}^*_{prev}\|^2 \quad \text{s.t.} \quad \mathbf{CF} \leq \mathbf{d} \tag{4}$$

The cost function (4) reflects a trade-off between three goals: driving the CoM dynamics to the desired values, minimising the forces used, and penalising deviations between the current QP solution and the solution at the previous time-step, $\mathbf{F}^*_{prev}$. The matrix $\mathbf{S}$ determines the relative priority in control over the rotational and translational motion, and the gains $\alpha > 0$ and $\beta > 0$ dictate the influence of the force normalisation and solution filtering. Constraints $\mathbf{CF} \leq \mathbf{d}$ are enforced to ensure that the optimised forces lie in the friction pyramid and that the normal forces lie within feasible bounds; these switch between support-leg and swing-leg bounds according to the scheduled contact, s_ϕ, as described previously.

Swing Leg Control

The Raibert heuristic (Raibert 1986) and a velocity-based feedback component from the capture point formulation (Pratt et al. 2006) are combined linearly to determine each footstep position from the corresponding hip location. The robot's lack of external environment sensors forces us to project the footstep locations onto a fictitious ground plane. As a result, the step location on the 2D ground plane for the foot is calculated from the hip of the robot by the following:

$$\mathbf{p}_{step,i} = \mathbf{p}_{h,i} + \underbrace{\frac{\mathbf{T}_{c_\phi}}{2}\dot{\mathbf{p}}_{c,d}}_{Raibertheuristic} + \underbrace{\sqrt{\frac{z_0}{\|\mathbf{g}\|}}(\dot{\mathbf{p}}_c - \dot{\mathbf{p}}_{c,d})}_{CapturePoint} \tag{5}$$

where $\mathbf{T}_{c_\phi}$ is the nominal scheduled contact phase (stance) time, z_0 is the nominal height of locomotion, and $\mathbf{p}_{h,i}$ provides the position of the corresponding hip i.

To determine the joint torques required to follow the Cartesian swing trajectory of each foot, a PD controller with a feed-forward term is utilised. The dynamics of the leg are used to calculate the feed-forward force:

$$\boldsymbol{\tau}_{ff,i} = \mathbf{J}_i^T \boldsymbol{\Lambda}_i ({}^{\mathfrak{B}}\alpha_{i,ref} - \dot{\mathbf{J}}_i \dot{\mathbf{q}}_i) + \mathbf{C}_i \dot{\mathbf{q}}_i) + \mathbf{G}_i \tag{6}$$

where $\mathbf{J}_i^T$ is the foot Jacobian, $\boldsymbol{\Lambda}_i$ is the operational space inertia matrix, ${}^{\mathfrak{B}}\alpha_{i,ref}$is the reference acceleration for the swing trajectory, $\mathbf{q}_i$ is a vector of joint configurations, $\mathbf{C}_i$ is the Coriolis matrix, and $\mathbf{G}_i$ is the torque due to gravity. The controller responsible for following swing trajectories is:

$$\boldsymbol{\tau}_i = \mathbf{J}_i^T \left[\mathbf{K}_p({}^{\mathfrak{B}}\mathbf{p}_{i,ref} - {}^{\mathfrak{B}}\mathbf{p}_i) + \mathbf{K}_d({}^{\mathfrak{B}}\boldsymbol{\nu}_{i,ref} - {}^{\mathfrak{B}}\boldsymbol{\nu}_i)\right] + \boldsymbol{\tau}_{ff,i} \tag{7}$$

where $\mathbf{K}_p$ and $\mathbf{K}_d$ are diagonal matrices of proportional and derivative gains.

To maintain stability in the swing-leg PD controller, the gains are adjusted based on the apparent mass of the leg in order to maintain a consistent natural frequency:

$$K_{p,j} = \omega_{des}^2 \boldsymbol{\Lambda}_{jj}(\mathbf{q}) \tag{8}$$

where $K_{p,j}$ is the j-th diagonal entry in $\mathbf{K}_p$, ω_{des} is the desired natural frequency, and $\boldsymbol{\Lambda}_{jj}$ is the j-th diagonal entry in the operational space inertia matrix.

Virtual Predictive Support Polygon

To take advantage of the combination of walking and running in legged locomotion, a virtual support polygon is defined to provide a desired center of mass location that is applicable across all gaits. By anticipating when a leg will make contact with the ground, the virtual support polygon is biased towards legs that are about to touch down and away from legs that are near the end of their contact phase. This approach allows the robot to maintain its forward momentum during the gait while using selected footstep locations to create a smooth reference trajectory that is automatically adapted to the available footholds in real-time.

State Estimation

Cheetah 3 estimates its body states using a two-stage sensor fusion algorithm that separates the estimation of body orientation from the estimation of body position and velocity. The algorithm first uses its inertial measurement unit (IMU) to estimate orientation. In the second stage, it combines accelerometer measurements with leg kinematics to estimate base position and velocity using a method inspired by (Bloesch et al. 2013). A similar two-stage approach has also been recently used for state estimation in the HRP2 humanoid, as described in (Flayols et al. 2017).

The first stage of the state estimation process uses an orientation filter (Mahony et al. 2008) that combines IMU gyro and accelerometer readings. The filter relies on the fact that the gyro provides a precise measurement of high-frequency orientation dynamics, while the presence of a gravity bias on the accelerometer allows it to correct any drift in the estimate at a lower frequency. Letting the orientation estimate ${}^0\hat{\mathbf{R}}_b$ as the orientation of the body relative to the i.c.s., the filter updates this estimate according to:

$$ {}^0\dot{\hat{\mathbf{R}}}_b = {}^0\hat{\mathbf{R}}_b \left[{}^b\omega_b + \kappa\omega_{corr} \right] \times \tag{9} $$

where $\kappa > 0$ is a correction gain and ω_{corr} is a correction angular velocity to align the accelerometer reading ab with its gravity bias:

$$ \omega_{corr} = \frac{\mathbf{a}_b}{\|\mathbf{a}_b\|} \times {}^0\hat{\mathbf{R}}_b^T \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{10} $$

The time constant of the de-drifting from this term can be approximated by κ^{-1}. In practice κ is heuristically decreased during highly-dynamic portions of the gait where $\|\mathbf{a}_b\| >> g$ with:

$$ \kappa = \kappa_{ref} \max(\min(1, 1 - \|\mathbf{a}_b - g\|/g), 0) \tag{11} $$

where g is the acceleration of gravity and κ_{ref} is chosen as $\kappa_{ref} = 0.1$. This method is effective at correcting drift in pitch and roll, but without fusing in exteroceptive information such as vision, error accumulation in yaw is inevitable (Fallon et al. 2014).

The second stage of the state estimation process combines the estimated orientation ${}^0\hat{\mathbf{R}}_b$ with kinematic measurements from the legs to estimate base position and velocity. Unlike previous state estimation techniques that approached this problem using an extended Kalman Filter (KF) (Bloesch et al. 2013), the two-stage approach allows this secondary fusion to be formulated as a standard KF. This simplifies the analysis and tuning of the filter and ensures that the filter equations will never diverge in finite time.

Braitenberg controller for the quadruped robot

In its simplest form (Ranó et al. 2018), a Braitenberg vehicle 3a implements positive taxis towards a stimulus by setting the velocity of each wheel (left v_l and right v_r) to a decreasing function of the stimulus perceived by the same side sensor (located at $\mathbf{x}_l$, left, and $\mathbf{x}_r$, right). This means that for a stimulus function defined on the plane of movement of the robot, $S(\mathbf{x}) : \Re^2 \rightarrow \Re^+$, the velocity of the left/right wheels is calculated as $v_{r/l} = F(S(\mathbf{x}_{r/l}))$, where $F(s) : \Re^+ \rightarrow \Re^+$ is a function with derivative $F'(s) \leq 0$. From the analysis of the approximated motion equation of the wheeled robot with active wheels (Rañó 2014) it can be seen that the forward speed (v) control can be substituted by a controller, $v = F(\mathbf{x})$ using as sensor measurement the value of $S(\mathbf{x})$ at the point between the sensors $\mathbf{x} = \frac{\mathbf{x}_l + \mathbf{x}_r}{2}$. The turning rate ($\dot{\theta}$) control for the wheeled vehicle works similarly to a controller measuring at $\mathbf{x}$ the gradient of the stimulus in the direction perpendicular to the vehicle scaled by the derivative of $F(s)$, $F'(s)$. Therefore the control of the wheeled robot is based on a unique functional connection $F(s)$ which defines the forward velocity profile, while its derivative defines the robot turning rate. In the case of the Braitenberg quadruped robot, the same approach is used to obtain the desired translational velocity, $\dot{\mathbf{p}}_d$, and turning rate, $\dot{\psi}_d$.

SIMULATIONS

The presented model and equations are implemented in a simulated environment. The results of simulating the Braitenberg 3a quadruped robot for various stimuli are presented in this section. The simulation is based on the CHAMP open-source development framework for building new quadrupedal robots and designing new control algorithms (Juan Miguel Jimeno 2022). The control system is based on the MIT Cheetah robot implementation of a hierarchical controller for highly dynamic locomotion using pattern modulation and impedance control. The CHAMP library is integrated with the robot operating system (ROS) (Quigley et al. 2009) navigation stack. The Gazebo 3D simulator (Koenig and Howard 2004) is used in conjunction with ROS to enable seamless simulations. Gazebo is one of the most used simulators among researchers for robotic applications, and it provides a robust physics engine, high-quality graphics, and convenient programmatic and graphical interfaces. In this perspective, ROS serves as the interface for the robot model, while Gazebo is used to simulate both the robot and its operational environment. These features can be used as integral parts of the proposed framework.

In our simulations, the smell is replaced by a light stimulus for the sake of simplicity, since the simulating odour is not available in Gazebo. The synthetic light sensory input is captured by two camera sensors mounted on the head of the robot. Each camera outputs an image (320×240 pixels size). To make each camera work like a light sensor, a script is made to convert an image into a binary representation. Then an average aggregated value is obtained

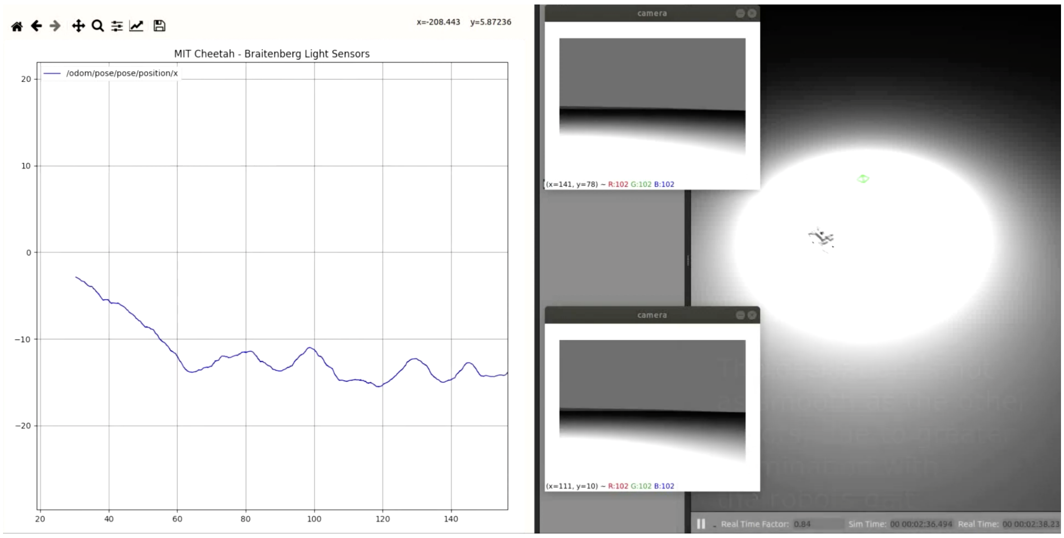

Figure 3. The Braitenberg quadruped robot converging toward a single source of light.

ranging from 0 to 255. The two cameras publish ROS topics with an illumination value, which changes as the robot is traversing the simulated environment. This is calculated continuously as the robot is moving.

In the simulated scenario, a single source of light is considered. The robot moves towards the light. A screenshots taken from the simulated scenario is shown in figure 3. On the right side of the figure, the simulated robot and the surrounding environment are depicted. The inputs from the two camera sensors are also visible. On the left side of the figure, a time plot for the robot displacement is depicted.

CONCLUSIONS AND FUTURE WORKS

This work demonstrated the potential for using bio-inspired controllers, based on the principles of Braitenberg vehicles, to enable quadrupeds robots to perform search and rescue (SAR) operations. By mimicking the strong sense of smell and efficient exploration capabilities of biological dogs, these robots could be valuable tools in such operations. Our work has shown that it is possible to use reactive navigation techniques, which directly couple the robot's sensors and motors, to give robots a similar level of sensory perception as dogs. Through simulations, we have shown that these controllers are effective at enabling different quadruped robot models, based on Braitenberg vehicle 3a, to orient themselves with the direction of a stimulus gradient and reach the maximum stimulus within a given range. For the purposes of our simulations, we have used light to mimic the scent that biological dogs use to perform SAR operations.

In future work, we plan to perform experiments with real quadruped robots to validate our simulation results. Additionally, we will explore the use of different stimuli, such as light, sound, and chemicals, to further extend the capabilities of these bio-inspired controllers. This represents an important step towards fully replicating the capabilities of biological dogs in a robotic form, and shows that the principles of Braitenberg vehicles can be applied to quadrupeds.

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