2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)
Beijing, China, November 6-9, 2018

A Proprioceptive, Force-Controlled, Non-Anthropomorphic Biped for Dynamic Locomotion

Jeffrey Yu, Joshua Hooks, Xiaoguang Zhang, Min Sung Ahn, and Dennis Hong[1]

Abstract— **The performance of traditional humanoid robots is often limited by their design, with high DoF limbs and stiff actuation complicating their dynamics and impeding their ability to operate in unsupervised environments. In response to these deficiencies, this paper introduces the Non-Anthropomorphic Biped: Version 2 (NABi-V2), a bipedal robot that is a departure from the conventional humanoid paradigm in its morphology and actuation method. That is, NABi-V2 is a platform with a unique leg configuration that is designed around high torque back-drivable electric actuators that provide proprioception and force control capabilities. This paper details the concept and design of this system, and presents a simple yet robust compositional controller for performing in place, two-legged pronking, a form of continuous jumping locomotion that is typically realized with series elastic or hydraulic actuation.**

I. INTRODUCTION

Humanoid robots that emulate the form and function of human beings have been a prevalent area of robotics research for several decades. Traditionally, these systems are realized with stiff, fully-actuated limbs, which are amenable to classical position-based control approaches [1]. These systems see the most success in fairly structured environments, where the robot's movements and interactions are either dynamically conservative or determined in advance. However, the human-fashioned spaces these robots are expected to occupy in the future are often quite unstructured and would necessitate the use of more active behaviors, meaning this type of approach may not be the most effective.

Recently, more capable legged systems have been developed that can operate over unregulated terrain through the use of dynamic running, hopping, trotting, and bounding behaviors enabled by hydraulics ([2], [3], [4]) or series elastic actuation ([5], [6]). These methods of actuation are customarily used for such gaits due to the fact that dynamic locomotion such as running and jumping requires high torques, and electric motor actuators typically achieve this through severe gearing that is easily damaged when confronted by the large impulses experienced during the ground impact following an aerial phase. These robotic systems with such added mechanical compliances usually have complex dynamics, making them difficult to control at best and restricted in their workspace and capabilities at worse. However, recent advances in electric motor technology have shown that electric actuators can be made to provide sufficient power and torque for dynamic locomotion without the need for high gearing. This facilitates mechanical designs with electric motors but no mechanical compliance that can achieve high fidelity force control, proprioceptive sensing, and impact resistance thanks to back-drivability.

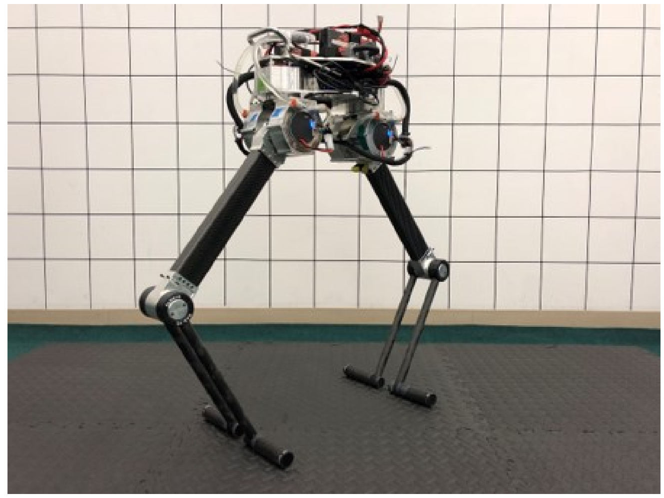


Fig. 1: The Non-Anthropomorphic Biped Version 2 (NABi-V2) lower body utilizes high torque, back-drivable actuators that provide high fidelity force control capabilities.

This back-drivable, high-torque actuator technology is predominantly applied to legged robotics in the form of dynamic quadrupeds like [7] on a large scale and quadrupeds and bipeds like [8] and [9] on a smaller scale, but is not often used on a large scale to power humanoids or bipeds in general. To this end, we aimed to incorporate the potential of this actuation method into the Non-Anthropomorphic Bipedal Robotic System (NABiRoS), a bipedal robot that attempts to tackle some of the difficulties of biped locomotion and control by rethinking the fundamental design of a bipedal robot. The result of this development is the Non-Anthropomorphic Biped: Version 2 (NABi-V2) shown in Fig. 1, a biped with a unique leg morphology that can perform dynamic behaviors such as two-legged pronking thanks to the use of proprioception and force control. The main contribution of this work is to present the new NABi-V2 platform and show how dynamic, event-based controllers can be implemented relatively simply on a biped with back-drivable electric actuation.

The remainder of the paper is organized as follows: Section II explains the non-anthropomorphic biped concept and discusses the adaptations made from the original NABiRoS. Section III presents an overview of the NABi-V2 system.

*This work was supported by the ONR through grant N00014-15-1-2064.
[1]All authors are with the Robotics and Mechanisms Laboratory (RoMeLa) at the University of California, Los Angeles (UCLA), Los Angeles, CA 90095, USA. The corresponding author can be reached at jeffcyu@ucla.edu.

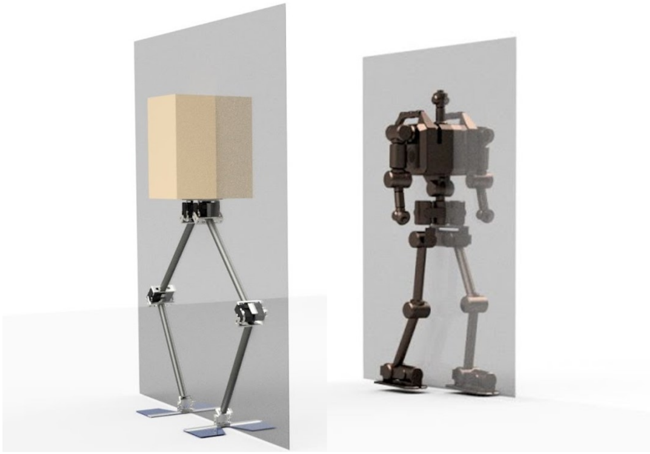


Fig. 2: Comparison of the original NABiRoS (left) and a more traditional humanoid (right) that shows the sagittal plane of each, as seen in [10].

Section IV details the implementation of two-legged pronking on the system. Section V reasons about the preliminary results of this system, and suggests some topics for future development. Section VI ends with concluding remarks.

II. NON-ANTHROPOMORPHIC BIPED CONCEPT

Conventional humanoid systems are designed to be highly versatile in function, but in implementation are often prohibitively slow, unsafe, or expensive due to the approach taken to perform bipedal locomotion. Traditional forward-walking bipedal locomotion on a typical humanoid with 6DoF legs is a heavily underactuated problem that typically leverages some form of dynamics compensation algorithm with inertial and force feedback. This form of walking is inherently difficult due to the fact that there is an offset in the hip joints that is perpendicular to the walking direction, creating undesirable oscillatory moments that can only be accounted for through accurate system modeling combined with sophisticated closed-loop feedback algorithms and high fidelity sensors, or by taking smaller steps. However, these moments do not appear when taking steps side to side, because the hip offset is in the same plane as the direction of travel. If the main mode of locomotion is sideways walking, the forward-facing knees are not being used, and can be rotated by ninety degrees so that the legs are aligned in a plane. By aligning the legs in the sagittal plane, forward walking can be achieved using the sideways walking motion. With the legs aligned in a plane, the ankle can be removed and replaced with a much simpler foot element.

This simple, 2DoF leg configuration was first featured on NABiRoS, a prototype biped with high-gear ratio servo actuators at the joints and a mechanical spring foot element that can walk by mimicking a linearized inverted pendulum, and perform two-legged pronking thanks to its series-compliant leg and foot [10]. NABiRoS, illustrated in Fig. 2, demonstrated that bipedal robots do not need to share the morphology of a humanoid to be able perform simple locomotion, but the original platform was limited to locomotion in a plane. Further investigation into how the NABiRoS platform could be adapted to achieve turning was done in [11], with the results showing that adding a third, yaw DoF at the hip allow for the simplest and most effective turning strategy.

While NABi-V2 shares the morphology of the original NABiRoS with the additional hip DoF, it differs in how it is actuated. NABi-V2 uses Back-drivable Electromagnetic Actuator for Robotics (BEAR) modules at each of its leg joints, while NABiRoS uses position controlled servos. Furthermore, NABi-V2 no longer needs a compliant foot element in series with the rest of the leg to perform more dynamic motions because compliance can be achieved through software in the BEAR modules.

III. SYSTEM OVERVIEW

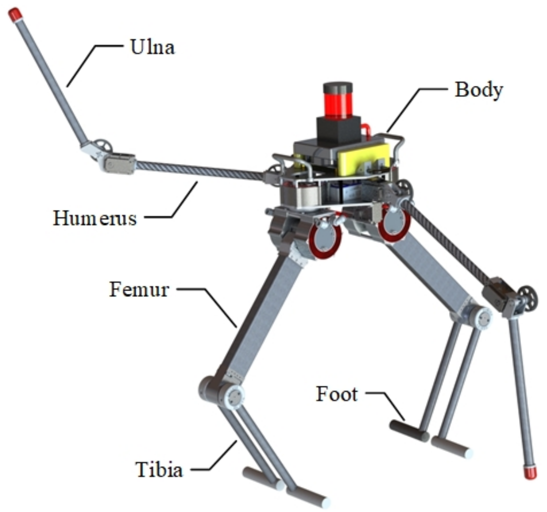
A. Design

NABi-V2 shares the same morphological characteristics as the original NABiRoS to continue to take advantage of the benefits that are inherent in the non-anthropomorphic design. However, it has a third yaw DoF at the hip, and its leg joints are all driven by back-drivable actuation modules that can provide significantly improved dynamic performance over most traditional position controlled servos. Additionally, NABi-V2 is planned to have a pair of 3-DoF arms with modular end-effectors that can mount assorted tools to enable NABi-V2 to perform various inspection and manipulation tasks. The arms can also be potentially used for locomotion and fall recovery, as was explored in [11]. The design and structure of NABi-V2 is shown in Fig. 3.

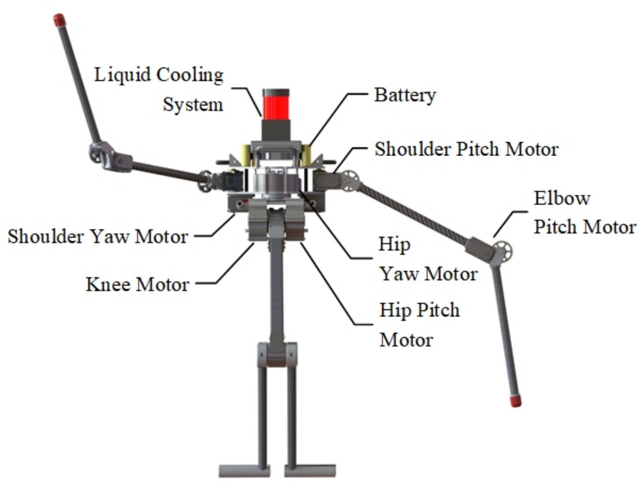
To maximize dynamic performance of NABi-V2, its legs are designed with minimal mass and inertia. The femur and tibia links are comprised of lightweight carbon fiber tubes epoxied to aluminum joints and comprise around 20% of the total robot mass. All leg actuators are located at the hip to minimize the inertia of the leg, so pair of 1:1 ratio pulleys with a timing belt are employed, as show in Fig. 4.

The carbon fiber tube on the femur links has a rectangular profile that covers the timing belt and shields the transmission from external contaminants and other external forces. A pair of tensioners located at each end of the femur link keep the belt under tension and prevent backlash that is typical in conventional gearboxes. NABi-V2 also takes advantage of the belt-pulley transmission by adopting a double-shin design that allows the knee joint to rotate continuously, enabling some creative methods for locomotion across certain obstacles as investigated in [12]. The lightweight carbon fiber and aluminum structure of the legs are also applied to the arms, but the arm actuators are standard geared servos located directly at the joints for simplicity. Currently, the arms are not attached to the NABi-V2 to simplify and expedite the development of locomotion control.

NABi-V2 carries two 3250mah 4S LiPo batteries that power all of its subsystems: an Intel NUC computer, a liquid cooling system comprised of a reservoir-pump assembly and



(a)



(b)

Fig. 3: NABi-V2 isometric view (a) showing key aspects of the non-anthropomorphic design, and a front view (b) detailing the layout of the actuation modules and associated subsystems.

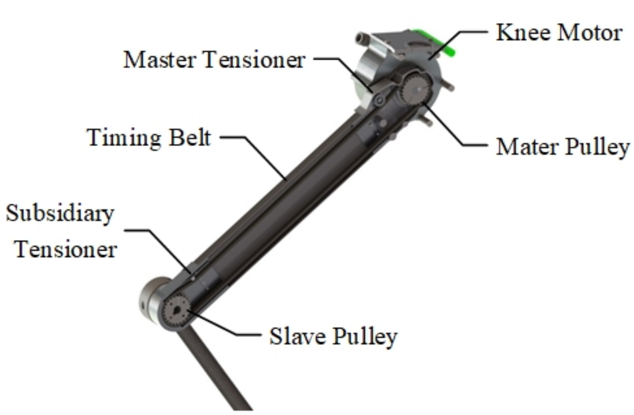


Fig. 4: Section view of femur link with the pulley transmission mechanism inside enabling continuous knee rotation.

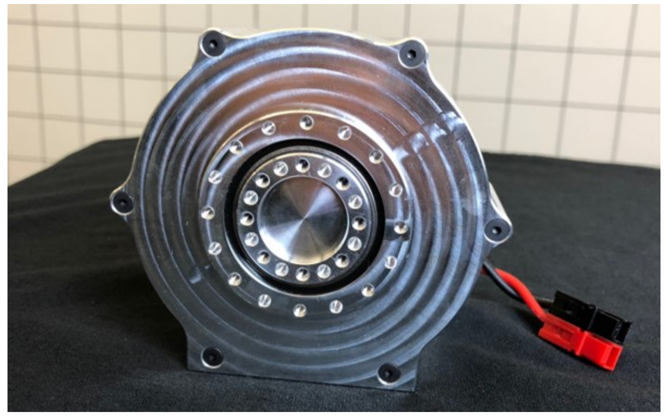


Fig. 5: The Back-drivable Electromagnetic Actuator for Robotics (BEAR) module used to power NABi-V2.

radiator-fan assembly (typically used in PC liquid cooling), a LORD MicroStrain 3DM-GX4-25 IMU, and its actuators.

B. Back-Driveable Actuation

To original NABiRoS was designed with high gear ratio position controlled servos, but was able to perform an energy efficient walking gait as well as pronking thanks to the addition of compliant feet that could store energy. However, these compliant feet were not equipped with any form of sensory feedback, so the system was unable to actively control the compliant behaviors of the system or detect certain discrete events like foot touchdown, meaning this series elasticity was forced to be used in a more passive capacity. Furthermore, the bandwidth of the servos was too poor to take full advantage of the elastic element, meaning the elasticity could only be utilized in a very specific set of motions. These are issues that NABi-V2 is able to avoid thanks to the use of back-drivable actuation.

NABi-V2 utilizes six Back-drivable Electromagnetic Actuator for Robotics (BEAR) modules to power its leg joints. The BEAR module, pictured in Fig. 5, was designed with legged robotics in mind, providing the speed, torque, and transmission transparency necessary for proprioceptive force control and impact mitigation. To achieve this, the BEAR module is built with a low gear ratio single phase planetary gearbox and a large motor with superior torque density characteristics. The power and control electronics are also custom made and packaged within the actuation module itself, improving modularity. The specifications of the BEAR module are shown in Table I

TABLE I: BEAR Specifications

Weight (g)	670
Gear Reduction	10:1
Voltage (V)	30
Max Current (A)	60
Peak Torque (Nm)	32
Cont. Torque	10
Max Velocity (rpm)	300

C. Software Architecture

The original NABiRoS software architecture is structured with simplicity and modularity as its focus to promote rapid development. However, to achieve stable proprioceptive force control while retaining the aforementioned characteristics, the architecture is modified to maximize speed by restructuring the architecture layout such that it supports concurrency. The different modules are shown in Fig. 6, with concurrently run processes highlighted.

The computer used to run NABi-V2 is equipped with an Intel Core i5-7260U @ 2.2 GHz with 8 GB of RAM. NABi-V2's software is written in Python 2.7 under Ubuntu 16.04, utilizing open-source libraries and optimized in-house built modules. Unlike other setups that may require a significant time from the user to prepare the machine, NABi-V2 can be readily set up under a Python virtual environment. This allows the code base to remain simple for many people to quickly get involved with the development.

Modularity of the architecture also invites multiple people to work on the development with minimal merge conflicts. By abstracting the details of each controller in one or more states in a trampoline based finite state machine (FSM), multiple people can simultaneously work on multiple controllers. Operations in each state is standardized by passing between states a 'virtual robot' object that resides on the stack. Then, different controllers can independently calculate their respective inputs and command the virtual robot using standardized method calls. The robot object then spins once to update its attributes and execute necessary methods, which includes updating the shared memory segment which is imperative for a fast control loop.

Concurrently, a hardware manager that is a dedicated process for each chain of limbs is run. The manager indefinitely runs a while loop sequence of communication with the POSIX shared memory segments that: 1. Read the state of the hardware and, with the semaphore, update the shared memory block that the hardware manager is writing to, 2. If necessary, with the semaphore, read from the shared memory block that the virtual robot writes to and write to the hardware. POSIX shared memory and semaphores were chosen to stay safe for potential multithreading and to keep semaphore overhead low. The hardware manager communicates with the hardware at maximum speed, and processes can be assigned to dedicated cores to further increase the communication frequency as seen in Table II, which shows an average frequency over 10,000 communications between the hardware manager and the two chains of limbs. Through this approach, we are able to achieve stable proprioceptive force control despite using a dynamically typed language with unpredictable delays.

TABLE II: Communication Frequency Comparison

Shared Core [Hz]		Dedicated Core [Hz]	
2026.99	2169.82	2289.47	2348.09

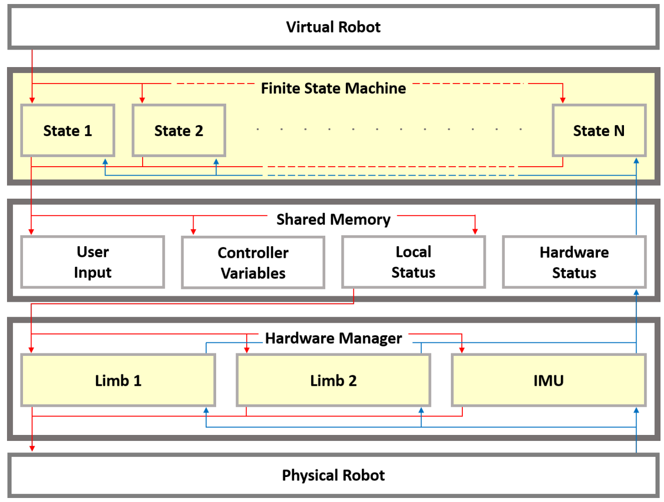


Fig. 6: NABi-V2 software architecture layout, with concurrently running processes highlighted in yellow.

IV. FORCE-CONTROLLED PRONKING

The overall design of NABi-V2 makes it an ideal platform for pursuing force/torque based control approaches, though position control can be used if desired. For NABi-V2, force control simply involves defining some desired force to be exerted by the end effector, then converting these forces to joint torques by first rotating the forces into the robot frame and then multiplying by a Jacobian as shown in equation (1).

$$\boldsymbol{\tau} = J_c R_{BN} \boldsymbol{F} \tag{1}$$

Where $\boldsymbol{\tau}$ is a vector of joint torques, J_c is the contact Jacobian relating joint rates to end effector (foot) velocities, R_{BN} is the rotation matrix that rotates the inertial frame into the robot body frame, and $\boldsymbol{F}$ is the force exerted by the end effector. This relationship yields a fairly simple model of NABi-V2 as a floating rigid body with massless legs that transfer forces from the ground, as shown in Fig. 7. The lightweight leg design of NABi-V2 facilitates this massless leg model, which is computationally simple and does not require very accurate measurements of link mass and inertia. The systems presented in [7] and [13] also use the Jacobian relationship for similar reasons. The following section details a simple controller that effectively make use of the BEAR modules to achieve two-legged pronking on NABi-V2.

A. Double Support

A key aspect of controlling legged robots is leveraging ground reaction forces at the feet to govern the system's overall posture and position. This is apparent when NABi-V2 is standing in double support, when it only has two point-foot contacts with the ground (when viewed orthogonal to the plane created by the legs). For this reason, an aggregated task-space PD controller was developed to control the ground reaction forces created by NABi-V2s feet during double support. The first portion of the controller applies a normal force that counteracts the weight of the robot and performs

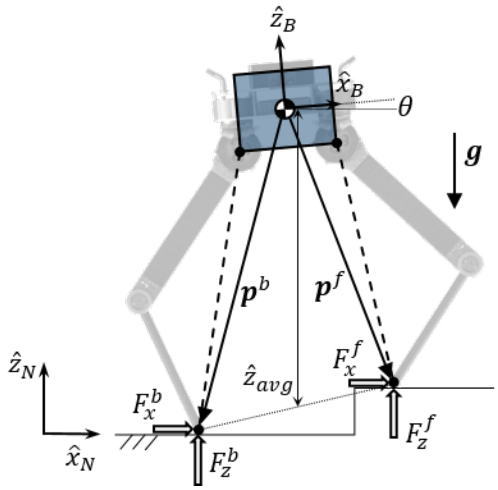


Fig. 7: NABi-V2 modeled as a floating rigid body with massless legs that transfer ground reaction forces to the body.

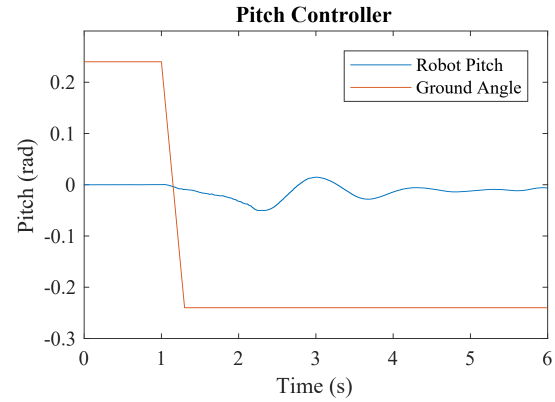


Fig. 8: The pitch controller is able to reject a step of 0.5rad when the ground angle is suddenly shifted.

task-space PD control around a nominal foot setpoint to account for disturbances and modeling inaccuracies.

$$\boldsymbol{F}^f_{grav} = \frac{p^b_x}{p^f_x + p^b_x} m\boldsymbol{g} \tag{2}$$

$$\boldsymbol{F}^b_{grav} = \frac{p^f_x}{p^f_x + p^b_x} m\boldsymbol{g} \tag{3}$$

$$\boldsymbol{F}^f_{ee} = K_p(\boldsymbol{p}^f_d - R_{BN}\boldsymbol{p}^f) + K_d(\dot{\boldsymbol{p}}^f_d - R_{BN}\dot{\boldsymbol{p}}^f) \tag{4}$$

$$\boldsymbol{F}^b_{ee} = K_p(\boldsymbol{p}^b_d - R_{BN}\boldsymbol{p}^b) + K_d(\dot{\boldsymbol{p}}^b_d - R_{BN}\dot{\boldsymbol{p}}^b) \tag{5}$$

Where the superscripts $i = \{f, b\}$ denote the front or back foot, K_p and K_d are diagonal gain matrices, $\boldsymbol{F}^i_{grav}$ and $\boldsymbol{F}^i_{ee}$ are the force contributions from gravity and end effector position feedback respectively, $\boldsymbol{p}^i_d = [p^i_{d,x}, p^i_{d,y}, p^i_{d,z}]^T$ and $\dot{\boldsymbol{p}}^i_d = [\dot{p}^i_{d,x}, \dot{p}^i_{d,y}, \dot{p}^i_{d,z}]^T$ are the desired position and velocity of the i^{th} end effector in the inertial frame, and $\boldsymbol{p}^i = [p^i_x, p^i_y, p^i_z]^T$ and $\dot{\boldsymbol{p}}^i = [\dot{p}^i_x, \dot{p}^i_y, \dot{p}^i_z]^T$ are the position and velocity vectors for the i^{th} end effector in the body frame. Note that the gravitational force is scaled by the normalized x components of the end effector positions, ensuring that no moment is created when accounting for the gravitational force. Now, double support over known terrain can be achieved by summing the gravity ($grav$) and end effector feedback (ee) contributions for each leg.

To achieve a balanced double support over unknown terrain, pitch (θ) and roll (ϕ) contributions are added to the force being generated by the legs:

$$F_{pitch} = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta}) \tag{6}$$

$$F_{roll} = K_p(\phi_d - \phi) + K_d(\dot{\phi}_d - \dot{\phi}) \tag{7}$$

For the pitch contribution, because the feet position cannot be predefined over unknown terrain, individual foot position feedback often resists the effort of the pitch controller. The solution to this was to take an average z position of the feet, z_{avg}, and replace the current z position of both foot with this average value, so $p^f_z = p^b_z = z_{avg}$ when the pitch controller is active over unknown terrain. This effectively creates a pivot point at the robot body that allows the legs to have different lengths. An example of the robot rejecting a sharp change in ground angle using the pitch controller is shown in Fig. 8.

One consideration when implementing the roll controller is the fact that NABi-V2 does not have an ankle joint, so any motion from the hip yaw joint will create an undesirable twisting motion of the foot on the ground. This resultant twisting combined with noise in the system can cause instabilities when the roll controller is active. However, once the robot has tipped significantly, the roll controller can help prevent a fall and/or recover from disturbances much faster as can be seen in Fig. 9. For this reason, the roll controller is only activated once a roll of 2 degrees is exceeded.

The total force $\boldsymbol{F}^i$ exerted by each leg can now be determined by simply summing the component controllers for each leg:

$$\boldsymbol{F}^f = \boldsymbol{F}^f_{grav} + \boldsymbol{F}^f_{ee} + [0, F_{roll}, F_{pitch}]^T \tag{8}$$

$$\boldsymbol{F}^b = \boldsymbol{F}^b_{grav} + \boldsymbol{F}^b_{ee} + [0, F_{roll}, -F_{pitch}]^T \tag{9}$$

The pitch contribution is added in equal and opposite magnitudes in the z component of the leg force to create a restorative moment about the y-axis, while the roll contribution is added to the y component of force to 'push' the robot back when it is tipping.

B. Compositional Pronking Controller

Continuous jumping on a legged robots has been an active field of research since Raibert instituted his event-based heuristic controller on a prismatic pneumatic actuator monoped [14]. Many systems have since been implemented to follow Raiberts paradigm, and the so called Raibert Controller is now commonly implemented to demonstrate the efficacy of various compliant and springy leg designs [15]. A similar approach is taken here to illustrate how force

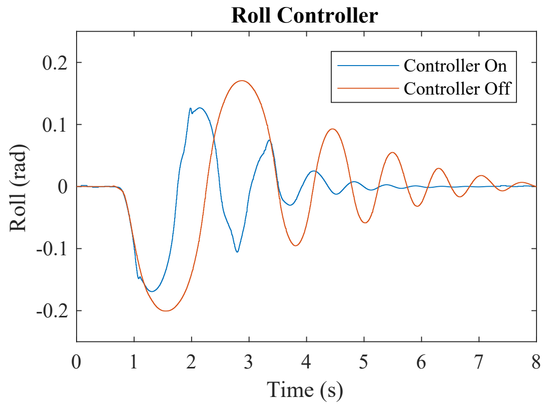


Fig. 9: System response to an impulsive lateral kick that induces roll in the body. When the controller is applied, the system stabilizes more quickly and can also prevent the system from tipping over.

control on the legs of NABi-V2 can be utilized to mimic a mechanical compliance.

The classical Raibert controller was an empirical controller that was comprised of three control modules that independently regulated different aspects of Raiberts hopping robots: the vertical jumping height, the horizontal velocity, and the orientation of the body. This sort of modular controller has been formalized as the composition of several templates in [16], which also discusses the assumptions necessary for stability.

The jumping controller utilized on NABi-V2 takes inspiration from Raiberts seminal work, but is modified slightly to accomplish vertical pronking; a form of jumping locomotion seen in nature where all feet are simultaneously lifted off and placed on the ground. For this form of jumping, NABi-V2 can be modeled as a floating rigid body with massless spring-damper legs attached at the hip. These massless leg springs are easily implemented on the robot by providing a foot setpoint, $\boldsymbol{p}_j^i$, that matches the length of the leg-spring for leg i in phase j, and then tuning the PD gains of the associated PD controller to mimic desired spring-damper qualities. The use of massless, springy legs in simple running and jumping models has been well documented for several decades, seeing recognition in both the robotics and biology communities [17].

For the proposed controller, separate modules are used to control the thrust applied at each leg and the orientation of the body. Like the Raibert Controller, vertical height is controlled by applying a constant thrust in the stance phase. This thrust is achieved by increasing the nominal rest length of the leg-spring by ΔL, thus injecting energy into the system in the form of leg-spring potential energy. However, unlike the original Raibert Controller, the thrust does not occur as soon as the foot contacts the ground. Instead, thrust is only applied after the leg-spring reaches its full compression. At this point, the body has reached its lowest point, or nadir, in the jumping cycle, and the thrust is applied. Thrust begins at the nadir rather than at touchdown because this provides a longer thrust stroke and a protracted stance phase, producing a higher apex and providing more time for the the body orientation to stabilize. The body orientation is controlled by the PD controller described previously and is activated as soon as touchdown occurs. Touchdown occurs after both feet have contacted the ground and is determined by measuring sharp jumps in displacement and velocity of the foot during flight.

The controller can be visualized using the diagram in Fig. 10. Proprioceptive data (motor current, angle, and rate) from a knee actuator are shown in Fig. 11 and demonstrate how the data is used to trigger events. When implementing the controller, the PD gains of the force controller as well as the thrust length of the jump were tuned empirically. The robot is able to stably jump continuously at a height of approximately 15cm as illustrated in Fig. 12.

V. DISCUSSION AND FUTURE WORK

A. The Energetic Cost of Compliance

While NABi-V2 demonstrates the effectiveness of high torque, low gear ratio actuation at performing dynamic motions that require compliant behavior, it is worth noting that this approach does sacrifice some of the benefits of using heavily geared electric actuators. For example, the nominal energy consumption of the system standing at idle is significantly higher than that of the similarly sized NABiRoS system, which uses conventional servos. This is because the only way for NABi-V2 to counteract gravity is for the BEAR modules to continuously provide torque (and thus, current) at the joints, while the traditional servos on NABiRoS can utilize the significant friction from the gearboxes in addition to the application of torque. However, when performing dynamic motions like pronking, it is possible for the BEAR module to actually regenerate significant amounts of current, something that is generally negligible on traditional servos. This means that NABi-V2 has the potential to be more efficient when in motion, while NABiRoS is more efficient when stationary. In any case, the benefits of the BEAR modules still outweigh the drawbacks, as NABiROS was never able to fully realize proprioceptive force control as NABi-V2 is, despite it's series elastic leg design.

B. Walking and Directional Locomotion

Classical walking algorithms on bipedal systems typically modeled the stance leg of the biped as a form of pendulum, and utilized the dynamics of said pendulum to dictate the control of the leg. Often, this produced time-dependent trajectories that would be 'played back' using high gain PD control on the servos of the robot. This rudimentary approach has since been adapted and improved to incorporate more feedback and optimization, but is often still the simplest and quickest way to develop a walking algorithm for a biped. NABiRoS utilized this form of walking controller, and was actually assisted by its compliant foot element when walking. However, applying this joint-space approach on NABi-V2 proved to be wildly inconsistent, resulting in the robot taking anywhere between one and three steps before

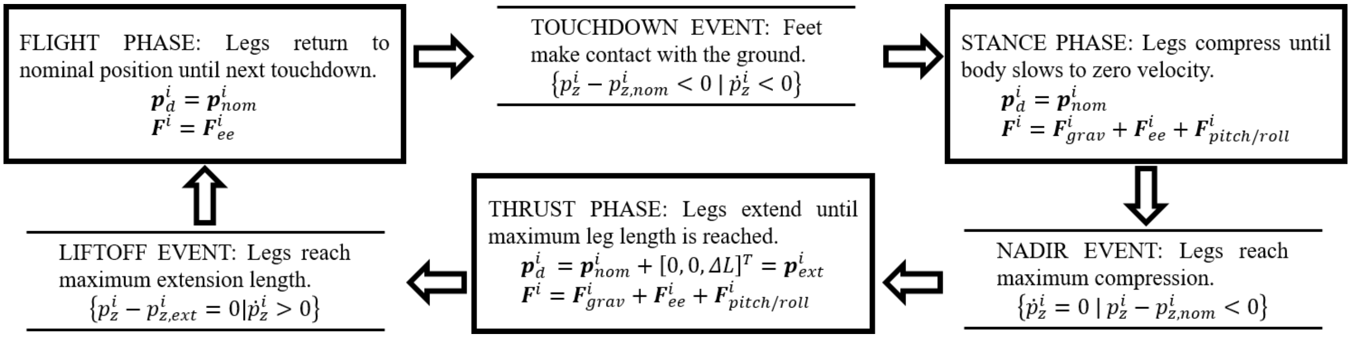


Fig. 10: Diagram showing the continuous time phases and discrete events that are used to perform the two-legged pronking. In each phase, the desired foot setpoint $\boldsymbol{p}_d^i$ is set to either the nominal (nom) configuration or the extended (ext) configuration. In flight, only (4) and (5) need to be used, but in stance and thrust the full (8) and (9) are necessary.

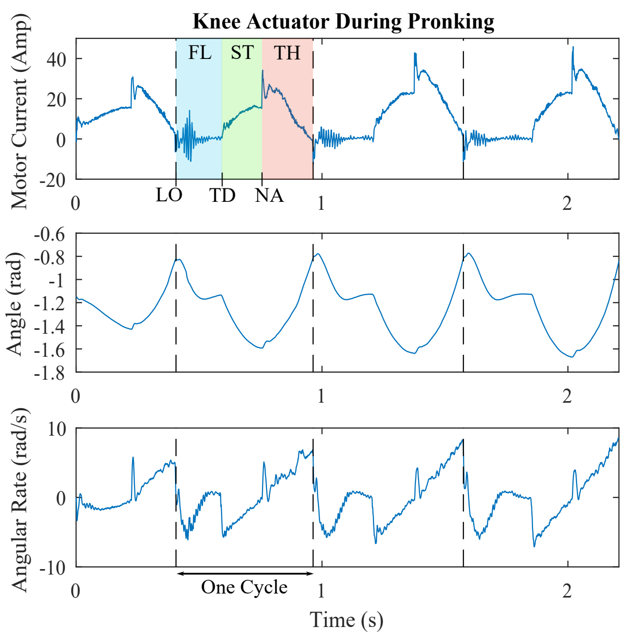


Fig. 11: Plots showing the motor current, angle, and rate of one knee actuator while pronking. Discrete events are typically triggered by abrupt changes in at least one of these proprioceptive attributes. The discrete events are labeled LO, TD, and NA for liftoff, touchdown, and nadir, respectively; the continuous phases are FL, ST, and TH for flight, stance, and thrust, respectively.

ultimately becoming ‘out of sync’ with the controller. The cause of this is likely the inherent compliance in the system reducing the fidelity of the position control capabilities in the form of unpredictable transients. Usually, these issues can be mitigated by having high damping which comes naturally with the high friction gearboxes of traditional servos, but is something that must be done through software on the BEAR modules, and is subject to factors such as sensor noise and control rate.

In the future, it would be possible to further optimize the robot control architecture and BEAR module firmware to allow for improved position control fidelity, but it may be more interesting and useful to instead embrace the compliant nature of the system and develop directional locomotion around it. Pronking already provides an interesting avenue of work that is reminiscent of Raibert’s classical hoppers, and may be amenable to the foot touchdown controller that was used on his monopods to control horizontal speed. This idea could be further extended to both walking and potentially running, in which the system would somewhat resemble a quadruped bounding as seen from the side.

C. Enhancing Proprioception

The back-drivable nature of the BEAR modules on NABi-V2 provide proprioceptive capabilities that are utilized when determining touchdown in the event-based pronking algorithm. However, the current touchdown detection implementation is relatively simplistic, relying on the activation of a couple of binary conditions to determine that touchdown has occurred. For future locomotion algorithms such as event-based walking or running, it is prudent to develop an improved form of touchdown detection that combines the proprioceptive capabilities of the BEAR module. A fusion of the the motor current, encoder position, and time has been shown to provide high accuracy touchdown detection in the face of various disturbances and noise in [18].

VI. CONCLUSION

NABi-V2 is a unique bipedal platform that deviates from traditional humanoid design in an attempt to provide a simple and robust platform for dynamic locomotion using proprioception and force control. The system’s morphology, actuation, and software architecture are all designed around this premise, resulting in the adoption of things like non-anthropomorphic leg design, BEAR modules, and concurrently run software processes. The outcome of this particular combination of features yielded a versatile legged platform that is capable of performing pronking using a Raibert-style compositional controller, a feat typically reserved for systems with mechanical springs or other forms of physical compliance. However, it was also found that the inherent compliance of NABi-V2 made traditional time and position dependent walking difficult, suggesting the advantages of

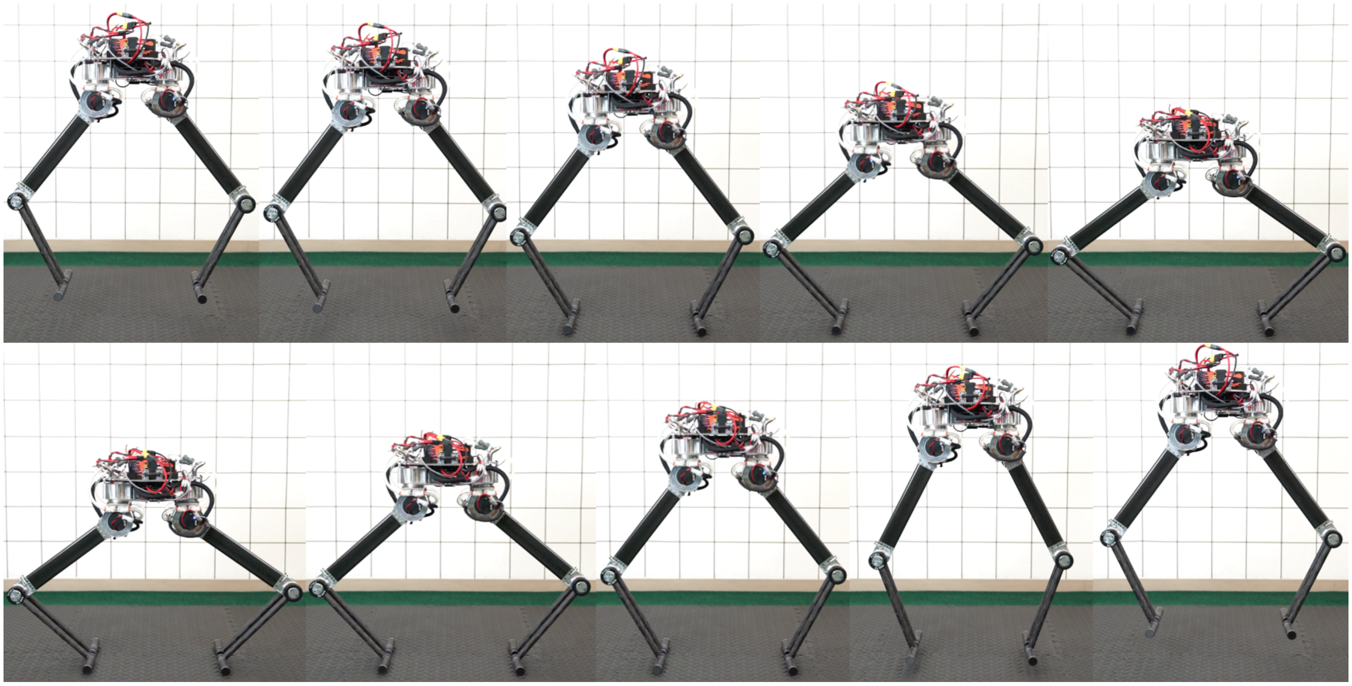


Fig. 12: NABi-V2 pronking.

using event-based controllers with the BEAR modules. Still, NABi-V2 represents a step towards the development of fully realized humanoids that have the potential to be used in a variety of unstructured environments and scenarios thanks to advances in actuation technology.

ACKNOWLEDGMENT

Special thanks to Taoyuanmin Zhu for designing and assembling the BEAR modules used on NABi-V2.

REFERENCES

[1] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The development of honda humanoid robot," in *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, vol. 2. IEEE, 1998, pp. 1321–1326.

[2] S. Kuindersma, R. Deits, M. Fallon, A. Valenzuela, H. Dai, F. Permenter, T. Koolen, P. Marion, and R. Tedrake, "Optimization-based locomotion planning, estimation, and control design for the atlas humanoid robot," *Autonomous Robots*, vol. 40, no. 3, pp. 429–455, 2016.

[3] M. Raibert, K. Blankespoor, G. Nelson, and R. Playter, "Bigdog, the rough-terrain quadruped robot," *IFAC Proceedings Volumes*, vol. 41, no. 2, pp. 10 822–10 825, 2008.

[4] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, "Design of hyq–a hydraulically and electrically actuated quadruped robot," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 225, no. 6, pp. 831–849, 2011.

[5] A. Ramezani, J. W. Hurst, K. A. Hamed, and J. W. Grizzle, "Performance analysis and feedback control of atrias, a three-dimensional bipedal robot," *Journal of Dynamic Systems, Measurement, and Control*, vol. 136, no. 2, p. 021012, 2014.

[6] M. Hutter, C. Gehring, D. Jud, A. Lauber, C. D. Bellicoso, V. Tsounis, J. Hwangbo, K. Bodie, P. Fankhauser, M. Bloesch, *et al.*, "Anymal-a highly mobile and dynamic quadrupedal robot," Robotic Systems Lab, ETH Zurich Zurich Switzerland, Tech. Rep., 2016.

[7] H.-W. Park, S. Park, and S. Kim, "Variable-speed quadrupedal bounding using impulse planning: Untethered high-speed 3d running of mit cheetah 2," in *Robotics and automation (ICRA), 2015 IEEE international conference on*. IEEE, 2015, pp. 5163–5170.

[8] G. D. Kenneally, A. De, and D. E. Koditschek, "Design principles for a family of direct-drive legged robots." *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 900–907, 2016.

[9] J. Ramos, B. Katz, M. Y. Chuah, and S. Kim, "Facilitating model-based control through software-hardware co-design," in *Robotics and automation (ICRA), 2018 IEEE international conference on*. IEEE, 2018, p. in press.

[10] J. Yu, J. Hooks, S. Ghassemi, A. Pogue, and D. Hong, "Investigation of a non-anthropomorphic bipedal robot with stability, agility, and simplicity," in *Ubiquitous Robots and Ambient Intelligence (URAI), 2016 13th International Conference on*. IEEE, 2016, pp. 11–15.

[11] J. Yu, J. Hooks, S. Ghassemi, and D. Hong, "Exploration of turning strategies for an unconventional non-anthropomorphic bipedal robot," in *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2017, pp. V05BT08A021–V05BT08A021.

[12] S. Ghassemi and D. Hong, "Investigation of a novel continuously rotating knee mechanism for legged robots," in *Ubiquitous Robots and Ambient Intelligence (URAI), 2018 15th International Conference on*, 2018.

[13] J. Pratt, C.-M. Chew, A. Torres, P. Dilworth, and G. Pratt, "Virtual model control: An intuitive approach for bipedal locomotion," *The International Journal of Robotics Research*, vol. 20, no. 2, pp. 129–143, 2001.

[14] M. H. Raibert, *Legged robots that balance*. MIT press, 1986.

[15] D. W. Haldane, J. K. Yim, and R. S. Fearing, "Repetitive extreme-acceleration (14-g) spatial jumping with salto-1p," in *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on*. IEEE, 2017, pp. 3345–3351.

[16] A. De and D. E. Koditschek, "Parallel composition of templates for tail-energized planar hopping," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*. IEEE, 2015, pp. 4562–4569.

[17] R. Blickhan, "The spring-mass model for running and hopping," *Journal of biomechanics*, vol. 22, no. 11-12, pp. 1217–1227, 1989.

[18] G. Bledt, P. M. Wensing, S. Ingersoll, and S. Kim, "Contact model fusion for event-based locomotion in unstructured terrains," in *2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, Australia, Submitted*, 2018.