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Human-Centered Development of Guide Dog Robots: Quiet and Stable Locomotion Control

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***Abstract*— A quadruped robot is a promising system that can offer assistance comparable to that of guide dogs due to its similar form factor. However, various challenges remain in making these robots a reliable option for blind and low-vision (BLV) individuals. Among these challenges, noise and jerky motion during walking are critical drawbacks of existing quadruped robots. While these issues have largely been overlooked in guide dog robot research, our interviews with guide dog handlers and trainers revealed that acoustic and physical disturbances can be particularly disruptive for BLV individuals, who rely heavily on environmental sounds for navigation. To address these issues, we developed a novel walking controller for slow stepping and smooth foot swing/contact while maintaining human walking speed, as well as robust and stable balance control. The controller integrates with a perception system to facilitate locomotion over non-flat terrains, such as stairs. Our controller was extensively tested on the Unitree Go1 robot and, when compared with other control methods, demonstrated significant noise reduction – half of the default locomotion controller. To evaluate the usability, workload, and perceived noise of the developed system from a user's perspective, we conducted indoor walking experiments. In these tests, participants compared our controller with the robot's default controller. The results demonstrated higher user acceptance of our controller, highlighting its potential to improve the overall user experience of robotic guide dogs. Video demonstration (best viewed with audio) available at: `https://guidedogrobot-stairclimbing.github.io`.**

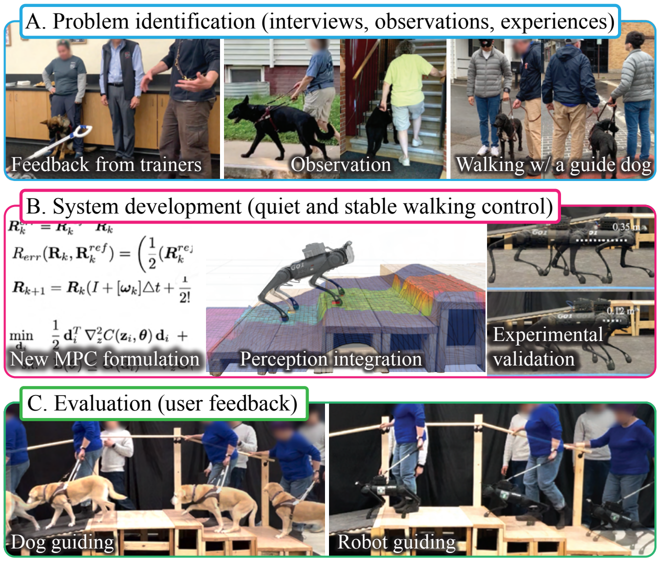

Fig. 1. **Human-centered Development of a Guide Dog Robot.** We employed a human-centered approach to develop a guide dog robot's locomotion controller, consisting of: (1) an initial exploratory study to identify critical unmet needs, (2) system development, and (3) user evaluation. One of our major contributions is the adoption of this complete, user-centric development process to advance the robot controller for blind and low-vision individuals.

I. INTRODUCTION

Guide dogs have long been recognized as an effective mobility aid, enhancing blind and low-vision (BLV) individuals' navigation capabilities, confidence, and independence [1], [2]. Despite these benefits, only a small fraction of the 250 million BLV individuals worldwide [3] work with guide dogs, primarily because of their limited availability. To resolve the issue, researchers have been developing robotic systems since 1976 [4]–[7]. Recent advances in quadruped robots have prompted investigations into robots with a dog–like form factor. However, beyond technical hurdles, numerous challenges persist in developing assistive systems for BLV individuals, including the complicated tasks of understanding users' needs and identifying critical gaps [8].

While several prior human-centered studies have uncovered various important aspects to consider for guide robots, most have focused on wheeled robots and navigation perspectives [6], [9]–[11]. Although several studies have suggested how to develop quadruped robots for BLV users [8], [12]–[14], the question of 'how the robot should walk' remains largely underexamined. In particular, Wang et al. emphasized the importance of noise suppression based on BLV individuals' responses to quadruped robots in comparison to wheeled systems, yet neither the criticality of low noise levels nor clear thresholds for acceptability were presented [14]. Kim et al. [13] compared user preferences between a default and an RL-based controller for a legged system, but without measured noise levels or quantitative control performance metrics, limiting its utility as a guideline for controller design.

Moreover, existing studies rarely offer a holistic perspective on related factors such as walking speed and robustness against pulling forces – issues that must be investigated in tandem, given that lowering noise often involves slowing the stepping frequency and potentially compromising both pace and stability. Equally important, detailed accounts of how guide dogs and handlers navigate uneven terrains (e.g., curbs or stairs) remain scarce, further underscoring the need for research on how a quadruped robot should walk to support

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real-world assistive contexts.

To identify technical gaps, set appropriate goals, and make informed development decisions, we conducted comprehensive exploratory studies. These studies included interviews with seven guide dog handlers and one trainer, demonstrations of a quadruped robot to gather feedback from stakeholders, and a two-and-a-half-hour blindfolded walking experience under expert supervision (Fig. 1). We found that BLV people often rely on subtle auditory cues for navigation, making the default robot controller's noise levels difficult to accept. We also discovered that their walking speed can be high – sometimes exceeding the typical pace of a sighted person – when they walk with a guide dog. Additionally, we learned how guide dogs behave when upcoming stairs or bumps are detected. These findings provide invaluable insights for designing a suitable locomotion controller for our guide dog robot.

Based on our exploratory studies, we prioritized the reduction of robot noise. Lowering the gait frequency and ensuring gentle touchdowns can effectively mitigate both backlash-induced and impact noise. One challenge is maintaining stability at slower gait frequencies, which necessitates robust balance control, as slower stepping generally reduces stability compared to more frequent stepping. Both RL-based strategy [13] and model predictive control (MPC)-based locomotion controller are equally valid approaches. In our case, we chose MPC methods due to three reasons: (1) although RL-based locomotion control has made significant progress, most studies prioritize agility [15]–[17] rather than the gentle walking we require. Conversely, MPC-based controllers [18] have demonstrated promising balance capability at slower stepping rates; (2) several prior RL-based controllers for quieter walking [13], [19] do not integrate terrain perception. Incorporating vision while maintaining quiet steps can pose substantial challenges because domain randomization, a standard technique to handle sim-to-real gaps, typically randomizes camera placement and thus introduces uncertainty in terrain height. Our experiments show that even a few centimeters of error in height measurements can result in leg stumping at touchdown; and (3) demonstrating specific robot behaviors – such as placing the front feet on the first staircase step to inform the handler of an upcoming incline – is easier with an optimization-based controller. We note that no fundamental limitations exist in either strategy; however, optimization-based approaches currently demonstrate promising capabilities and offer convenient features, such as direct management of swing leg motion.

Despite the promise of optimization-based control, no existing MPC formulation [18], [20], [21] explicitly addresses a noise suppression issue alongside vision-based walking. Through extensive comparison of various formulations, we concluded: (1) accurately modeling angular motion without simplification is beneficial, (2) a high update frequency is essential, and (3) separately managing swing foot control is especially advantageous for non-flat terrain. We developed a walking controller comprising a real-time sequential quadratic programming (SQP)-based Nonlinear Model Predictive Control (NMPC) and a whole-body impulse controller (WBIC) [20], preserving the nonlinear angular dynamics via an $\mathcal{SO}(3)$ representation similar to [22] and achieve a high update frequency by using real-time SQP [23].

TABLE I

INTERVIEW AND OBSERVATION SESSION PARTICIPANT DEMOGRAPHICS

ID	Age	Gender	Vision Level	Mobility Aid	Experience (GD yrs*)
H01	61	F	Totally blind	Guide dog	36
H02	69	F	Legally blind	Guide dog	30
H03	63	M	Totally blind	Guide dog	11
H04	69	M	Totally blind	Guide dog	30
H05	69	M	Totally blind	Guide dog	53
H06	59	M	Totally blind	Guide dog	21
H07	64	F	Totally blind	Guide dog	6
T01	58	M	-	-	35

* Indicates the total years participants spent working with guide dogs as handlers (H) and training guide dogs as trainers (T).

Our new controller accomplishes noise reduction of up to 10 dB compared to the robot's default controllers. Compared with the quadruped robot walking presented in [19] and wheeled systems tested in [14], our controller exhibits lower noise levels. To evaluate these improvements from the user's perspective, we recruited four guide dog handlers to compare two different controllers in flat, stair, and ramp conditions, assessing noise, usability, and workload. Their feedback emphasized a noticeably lower noise level, which they highly valued. All four BLV participants reported that our locomotion controller significantly reduced noise, offered a perceived workload comparable to a guide dog, increased satisfaction, and facilitated comfortable stair climbing. Consistent with common usage, we will use the term *guide dog* instead of the formal *dog guide* throughout this paper.

The primary contributions of this paper are threefold: 1) identifying robot control elements required to enhance user experience during walking and stair climbing with a guide dog robot, grounded in semi-structured interviews, observational, and participatory sessions with stakeholders, 2) developing a perception-based locomotion control framework that can substantially reduce noise, achieving up to a 50% reduction in noise level compared to existing controllers, and 3) a comprehensive, user-centric evaluation that assesses noise, usability, and workload with BLV people.

II. LESSONS LEARNED FROM STAKEHOLDERS

Our exploratory study aimed to identify technical gaps in improving the user experience for BLV individuals when walking with a guide dog robot. To achieve this, we conducted semi-structured interviews and observation sessions with guide dog trainers and handlers. Furthermore, we also participated in blindfolded walking with guide dogs under the trainer's supervision to obtain a lively experience of how animal guide dogs assist their handlers.

A. Exploratory User Study Design

1) Participants: We recruited four guide dog handlers and two professional guide dog trainers. Handler inclusion

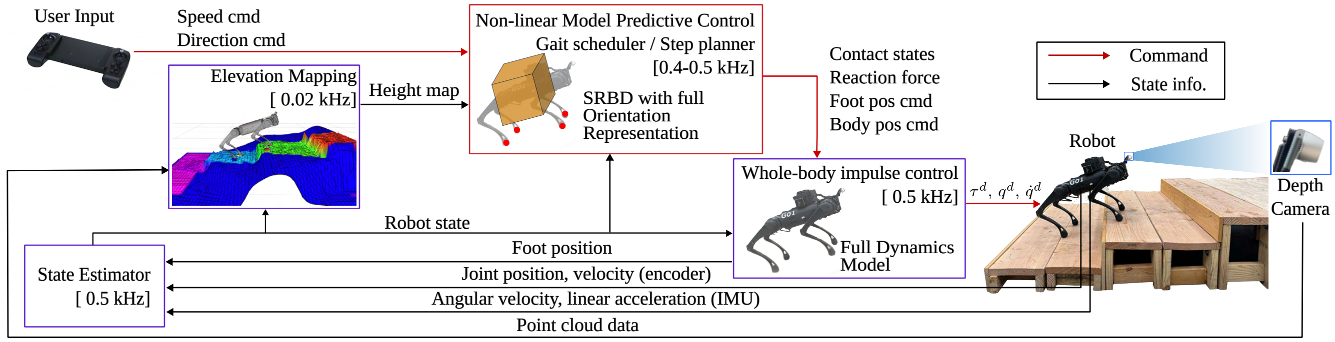


Fig. 2. **Overall Control Framework.** Our guide dog controller uses an NMPC+WBIC architecture. The NMPC incorporates a single-rigid-body model with full orientation dynamics to enable better orientation control and computes the required reaction forces, which are then passed to the WBIC. The WBIC generates feedforward torques, as well as desired joint positions and velocities, which are subsequently fed into the robot's onboard motor controller. For stair climbing, the robot is equipped with a RealSense D435 camera, and the captured point clouds are processed into a height map using Elevation Mapping.

criteria were (1) visual acuity of 20/200 or worse (Social Security Act §1614 [24]) and (2) at least six months of guide dog experience. Trainers had a minimum of five years of professional experience. Participant demographics are shown in Table I.

2) *Procedure:* Interview questions were co-designed with a guide dog handler and trainer, focusing on handler–dog interactions and animal guide dog functionalities. During observation sessions, participants navigated familiar routes with their guide dogs covering both indoor and outdoor environments, providing live demonstrations of real-world challenges and interactions. This included climbing up stairs of a building and ascending staircases to ride a bus. Trainers also showcased specialized training techniques, emphasizing how handlers work with their dogs in daily life.

B. *Findings*

1) *Noise: Can we use the robot's off-the-shelf locomotion controller?:* Handlers stressed the importance of auditory cues—such as vehicle sounds and wall echoes—for orientation. Noise from off-the-shelf quadruped controllers risks masking these cues, with even low-level buzzing disrupting natural navigation. As H03 remarked, "The noise is a little distracting. [...] You're not gonna sneak up on somebody that's for sure." Consistent with prior studies [13], [14], participants noted that noise undermines awareness and confidence, making suppression a critical requirement.

2) *Walking speed: Do blind people walk slower to be careful?:* Contrary to common assumptions, handlers preferred maintaining a normal or faster pace, comparable to sighted walkers. As H01 noted: "I walk fast with him. [...] Well, I like moving that fast." This highlights the need for guide-dog robots to support a wide range of walking speeds while ensuring safety and comfort.

3) *Stair Climbing: How do guide dogs assist stair climbing?:* Based on the observation of H01 climbing up stairs and H02 climbing up bus stairs with their guide dogs, we noticed certain promised sequences for safe stair climbing. Handlers perceived staircases through their harness, delivering the subtle movement of their dogs. As H01 explained, her guide dog stops after stepping on the first stair, allowing her to notice the presence of stairs ahead by detecting the tilt of the handle.

> "He stopped on the first step when he was on it. [...] I kicked it with my toe and I knew it was the stairs. I knew they were upstairs because he put his paws up. Versus down, I could tell if it was up or down on that first step." - **H01**

In summary, our findings highlight the critical need for a locomotion controller that can achieve high walking speeds ($0.6\,\mathrm{m/s}$ to $1.2\,\mathrm{m/s}$) and stair-climbing capabilities without producing disturbing noise or jerky movements. These insights guided the development of a user-centric locomotion controller tailored to BLV individuals.

III. CONTROL FRAMEWORK

A. *Real-time Nonlinear MPC*

To develop a noise-suppressed guide dog locomotion controller, we aimed to reduce stepping frequency and ensure gentle foot contacts using a combined NMPC+WBIC architecture (Fig. 2). The NMPC, with full orientation dynamics, is solved via single-iteration SQP, where the inner quadratic program is efficiently sovled by ADMM, enabling update rates up to 500 Hz for low latency and improved stability. WBIC then tracks NMPC reaction forces while managing foot-swing trajectories, producing smoother, quieter locomotion. To accurately represent angular motion, we used $\mathcal{SO}(3)$ representation similar to [25]. The state vector for the MPC is defined as:

$$\mathbf{x} = [\mathbf{p}^\top \quad \mathbf{R_{vec}} \quad \mathbf{v}^\top \quad \boldsymbol{\omega}^\top]^\top, \tag{1}$$

where $\mathbf{p} \in \mathbb{R}^3$, $\mathbf{v} \in \mathbb{R}^3$, $\mathbf{R_{vec}} \in \mathbb{R}^9$, and $\boldsymbol{\omega} \in \mathbb{R}^3$ are position, velocity, vectorized orientation matrix and angular velocity of the single rigid body. The cost function to be minimized is:

$$\min_{\mathbf{p}_k, \mathbf{f}_k} \quad \sum_{k=1}^{N} ref^{err}(\mathbf{x}_k, \mathbf{x}_k^{ref}) + \|\mathbf{f}_k - \mathbf{f}_k^{ref}\|^2_{\boldsymbol{Q_f}}$$

$$
\begin{aligned}
\text{where}\quad ref^{err} &= \|\mathbf{p}_k - \mathbf{p}_k^{ref}\|^2_{\boldsymbol{Q_p}} + \|\mathbf{v}_k - \mathbf{v}_k^{ref}\|^2_{\boldsymbol{Q_v}} \\
&\quad + \|\boldsymbol{\omega}_k - \boldsymbol{\omega}_k^{ref}\|^2_{\boldsymbol{Q_\omega}} + \|R_{err}(\mathbf{R}_k, \mathbf{R}_k^{ref})\|^2_{\boldsymbol{Q_R}} \\
\text{s.t.}\quad & \mathbf{x}_{k+1} = f_k^d(\mathbf{x}_k, \mathbf{f}_k), && \text{(dynamics)} \\
& -\mu f_{k,i,z} \le f_{k,i,x} \le \mu f_{k,i,z}, \\
& -\mu f_{k,i,z} \le f_{k,i,y} \le \mu f_{k,i,z}, && \text{(friction cone)} \\
& 0 \le f_{k,i,z} \le f_{max}, && \text{(reaction force)} \\
& f_{k,i,z}(1 - c_{k,i}) = 0, && \text{(contact scheduling)}
\end{aligned}
$$

where $\mathbf{x}_k^{ref} \in \mathbb{R}^{18}$ and $\mathbf{f}_k^{ref} \in \mathbb{R}^{12}$ are the reference for the state and reaction force, respectively. $\boldsymbol{Q_p}$, $\boldsymbol{Q_v}$, $\boldsymbol{Q_\omega}$, $\boldsymbol{Q_R}$ and $\boldsymbol{Q_f}$ are the corresponding diagonal weight matrices. f_k^d is the forward dynamics for a single rigid body, and c_k presents a contact schedule specified by a user. The reference reaction forces $\mathbf{f}_k^{ref}$ are simply set as vertical reaction forces that support the robot's weight according to the contact schedule. $\mathbf{x}_k^{ref}$ are computed by integrating the current state forward given a commanded base velocity. Except for the orientation, reference errors are L2 norm of the difference between the state and reference. The orientation error $\boldsymbol{R}_k^{err}$ is given as $\boldsymbol{R}_k^{err} = \boldsymbol{R}_k^{ref\top} \boldsymbol{R}_k$ where $\boldsymbol{R}_k^{ref}$ and $\boldsymbol{R}_k$ is the desired and actual orientation matrix at k step. To get vectorized orientation error, we transform $\boldsymbol{R}_k^{err}$ to $\mathfrak{so}(3)$ using

$$
R_{err}(\mathbf{R}_k, \mathbf{R}_k^{ref}) = \left(\frac{1}{2} (\boldsymbol{R}_k^{ref\top} \boldsymbol{R}_k - \boldsymbol{R}_k^\top \boldsymbol{R}_k^{ref}) \right)^\vee, \quad (2)
$$

where $(\cdot)^\vee : \mathfrak{so}(3) \to \mathbb{R}^3$ is the inverse of the skew function. The only simplification here is $\theta_k^{err} \approx \sin\theta_k^{err}$ based on the small orientation error assumption. The base orientation update uses a third-order Taylor expansion of the matrix exponential:

$$
\boldsymbol{R}_{k+1} = \boldsymbol{R}_k(I + [\boldsymbol{\omega}_k]\triangle t + \frac{1}{2!}[\boldsymbol{\omega}_k]^2 \triangle t^2 + \frac{1}{3!}[\boldsymbol{\omega}_k]^3 \triangle t^3). \quad (3)
$$

Since high MPC update rates are crucial for stability at low gait frequencies, we adopt real-time Sequential Quadratic Programming (SQP) [23], recently applied in robot control [21], [26]. The key idea is to use intermediate SQP iterations without waiting for full convergence, approximating the NMPC problem as a quadratic program (QP):

$$
\begin{aligned}
\min_{\mathbf{d}_i} \quad & \frac{1}{2} \mathbf{d}_i^T \nabla_z^2 C(\mathbf{z}_i, \boldsymbol{\theta})\, \mathbf{d}_i \;+\; \nabla_z C(\mathbf{z}_i, \boldsymbol{\theta})^T \mathbf{d}_i, \\
\text{s.t.} \quad & \mathbf{L}(\boldsymbol{\theta}) \le \boldsymbol{G}(\mathbf{d}_i) + \nabla_z \boldsymbol{G}(\mathbf{z}_i, \boldsymbol{\theta})\, d_i \le \mathbf{U}(\boldsymbol{\theta}),
\end{aligned} \quad (4)
$$

which are derived from the original equations:

$$
\begin{aligned}
\min_{\mathbf{z}} \quad & C(\mathbf{z}, \boldsymbol{\theta}) \\
\text{s.t.} \quad & \mathbf{L}(\boldsymbol{\theta}) \le \boldsymbol{G}(\mathbf{z}, \boldsymbol{\theta}) \le \mathbf{U}(\boldsymbol{\theta}),
\end{aligned} \quad (5)
$$

where $\mathbf{z}$ and $\boldsymbol{\theta}$ is the decision variable and the parameter vector. $\boldsymbol{G}(\mathbf{z})$ is the constraints with the lower bound $\mathbf{L}(\boldsymbol{\theta})$ and upper bound $\mathbf{U}(\boldsymbol{\theta})$.

In approximated QP (4), $\mathbf{d}_i$ is the step direction, $\nabla_z^2 C(\cdot)$ is the Gauss-Newton Hessian of the cost function $C(\cdot)$. $\nabla_z C(\cdot)$ is the gradient of $C(\cdot)$ and $\nabla_z \boldsymbol{G}(\cdot)$ is the Jacobian of $\boldsymbol{G}(\cdot)$. The cost function is a second-order Taylor approximation and the constraint is a linear approximation. Once QP finds $\mathbf{d}_i$, the decision variable is updated as: $\boldsymbol{z}_{i+1} = \boldsymbol{z}_i + \alpha_i \boldsymbol{d}_i$, where α is a step size found based on a line search algorithm from [21]. In standard SQP, iterations continue until $\boldsymbol{z}$ converges to a local minimum. In real-time SQP, however, only the first $\boldsymbol{z}$ (covering the horizon) is used for control, and the premature solution warm-starts the next problem as the robot advances. This strategy, shown effective in [26] and in our study, enables real-time control. Finally, WBIC is used to compute the final joint commands, as in [20].

B. Stair climbing

To handle non-flat terrains such as stairs, we integrated stair-climbing into the controller. Following [27], a 2.5D height map guides landing location and height adjustment, with local modifications to avoid stepping on stair edges by selecting regions with near-vertical normals. For BLV guidance, we emulate guide-dog behavior by pausing at the staircase entrance: the robot halts when its front feet contact the first step and resumes climbing once the user is ready.

IV. CONTROLLER EVALUATION

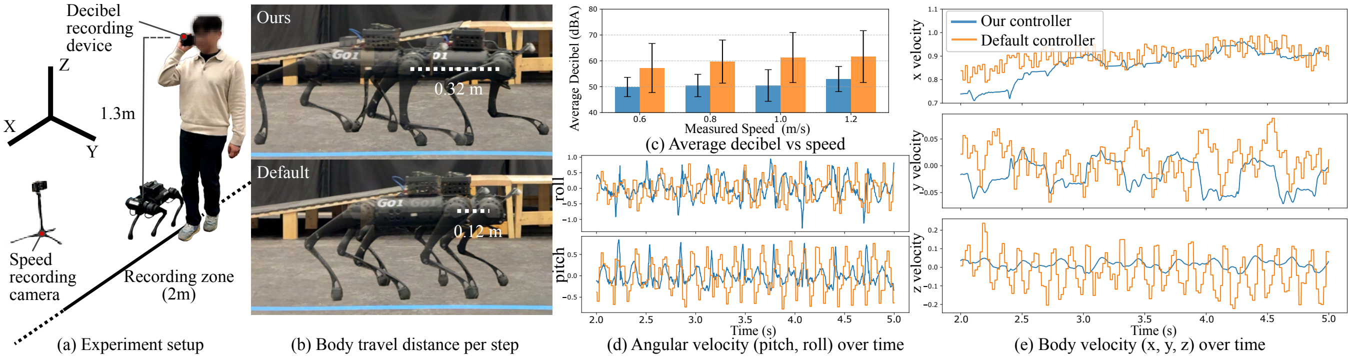
We evaluated the proposed controller through extensive hardware tests. Gradients and Hessians of the MPC cost and constraints (Eq. (4)) were computed via CasADi [28], and each MPC iteration was solved as a QP using OSQP [29], corresponding to a single SQP step. Unlike fixed-frequency implementations, our MPC runs on a separate thread, launching a new iteration immediately after the previous one, which reduces delay and improves balance. Each iteration is warm-started from the previous solution, as problem changes are minor. A QP solve requires 2 ms, yielding 400–500 Hz update rates. WBIC runs in the main control loop at 500 Hz, generating joint torque, position, and velocity commands, which are sent to the robot via the Unitree SDK.

A. Hardware Experiments

We evaluated our controller on a Unitree Go1 robot equipped with an onboard Beelink SEi12 PC (12th Gen i7-12450H), powered via a 24V–19V buck converter. The MPC horizon was set to 24 steps with a 0.026 s timestep, yielding a 0.286 s swing phase in trot gait.

To compare noise against the default controller, we measured sound levels at varying walking speeds. A researcher walked beside the robot, recording audio at ear level with a smartphone (Fig. 3a), while the robot traversed a two-meter noise-recording zone. A camera simultaneously captured entry/exit times to validate walking speed. Noise was benchmarked at four speeds (0.6–1.2 $\mathrm{m/s}$). Our controller is significantly quieter than the default controller (Fig. 3c), averaging 50 dB lower than the RL-based Anymal controller [19] and even wheeled systems (65 dB [14]), which were reported to be preferable for their lower noise.

Due to a slower gait frequency, in each step the controller covers more distance: at 1.0 $\mathrm{m/s}$ it achieves ~ 0.32 m per step versus $\sim$ 0.12 m for the default controller (Fig. 3b). Despite the longer body movement during the extended



(a) Experiment setup

(b) Body travel distance per step

(c) Average decibel vs speed

(d) Angular velocity (pitch, roll) over time

(e) Body velocity (x, y, z) over time

Fig. 3. **Hardware Experiment Results.** (a) To accurately measure the noise BLV individuals hear during walking, a person records the decibel value at his ear level while following the robot. (b) Both controllers (Our vs Default) are traveling at 1 m/s. The slower gait requires our controller to travel more distance within a single step. (c) On average, our controller has achieve a 10 decibel reduction. (d) We observed that angular velocity amplitudes of each controller are similar or even less sometimes. This shows our approach maintains comparable or better orientation control while having slower gait frequency. (e) Our controller shows better performance in maintaining the body velocity.

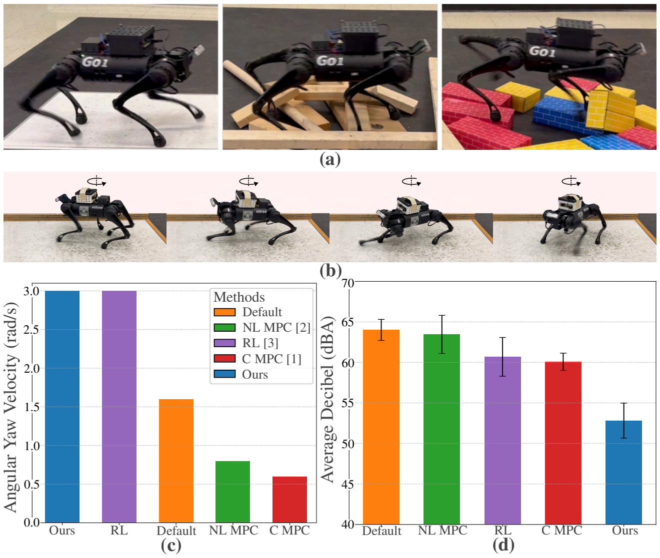
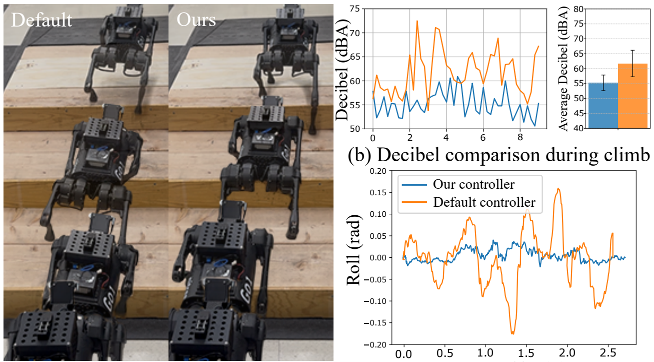


Fig. 4. **Comparison Experiments**. (a) Robust walking across slippery surfaces, wood blocks, and cardboard boxes.(b) The controller recovers balance after slips. (c) Outperformed all other optimization-based methods and is comparable to RL, known for excelling on slippery surfaces. (d) Additional noise tests showed it remains the quietest among all methods.

two-contact stance period, our method exhibits superior balance control showing fewer oscillations in both orientation (Fig. 3d) and linear velocity (Fig. 3e). Furthermore, the smoother velocity profile lowers noise and yields motion more consistent with guide-dog behavior, as noted in our user study.

We evaluated our controller on a stair-climbing task against the default controller. A custom staircase with 13 cm rise and 60 cm tread was built, since the Go1's short legs exhibited unstable locomotion on standard 18 cm stairs. Terrain perception was provided by a front-mounted Realsense D435, with depth data converted into a 2.5D elevation map using Elevation Mapping [30]. Based on this map, our controller adjusted foot landing heights, enabling lighter contacts and improved stability. As shown in Fig. 5a, and 5c, the default controller exhibited excessive roll during climbing, whereas our controller maintained balance and reduced noise (Fig. 5b).



(a) Stair climbing sequence

(b) Decibel comparison during climb

(c) Orientation (roll) over position (x)

Fig. 5. **Stair Climbing Tests.** Comparison of the default and proposed controllers on a 12.7 cm rise, 60 cm tread stair-climbing task, demonstrating our controller improves stability, reduces roll, and lowers noise.

In the forward walking test, our controller successfully traversed a whiteboard coated with soapy water, wooden blocks of varying dimensions, and a pile of cardboard boxes (see Fig. 4(a)) without a single failure across ten trials. We compared the robustness of our controller against leading optimization-based methods—Convex MPC [20] and Nonlinear MPC [21]—as well as an RL-based method with a noise reduction reward [13]. For consistency, all controllers operated at a gait frequency of approximately 2 Hz (except the default controller, due to limited low-level code access). In the robustness comparison test, we let the robot rotate on a slippery board until failure occurred. Despite frequent slips (see Fig. 4(b)), our controller maintained balance and successfully recovered at yaw angular velocities exceeding 3.0rad/s, comparable to the RL method, whereas the optimization-based methods lost balance before reaching the maximum yaw velocity (see Fig. 4(c)). We also compare acoustic noise during straight-line walking on flat terrain. As illustrated in Fig. 4 (d), our controller consistently produced substantially lower noise levels compared to all baseline

TABLE II
USER STUDY PARTICIPANT DEMOGRAPHICS

ID	Age	Gender	Vision Level	Aid	Experience (GD yrs* / Robot†)
RH01	63	F	Totally blind	Dog	33 / ✓
RH02	66	F	Legally blind	Dog	9 / ✗
RH03	66	M	Totally blind	Dog	13 / ✓
RH04	72	F	Legally blind	Dog	29 / ✓

* Indicates the number of total years the participant worked with guide dogs.
† Denotes the experience of walking with a guide dog robot prior to this study.

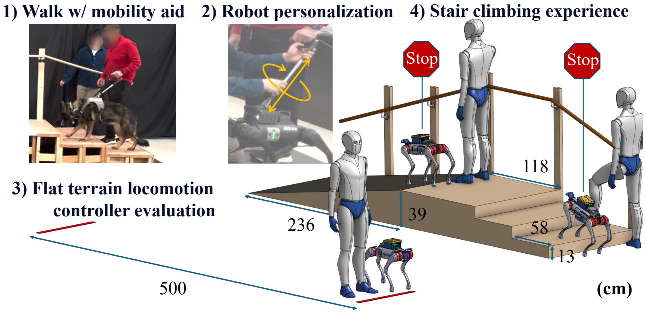


Fig. 6. **User Study Procedure and Setup.** The study consists of four sequential phases and is conducted in our lab space, which is equipped with a custom-designed structure featuring a staircase and a ramp. We finalized this setup based on feedback from a guide dog handler regarding the test environment before conducting the user study.

methods.

V. USER STUDY

We conducted a mixed-methods user study, approved by the university IRB, to evaluate whether our quiet locomotion controller and stair-climbing functionality address challenges identified in the exploratory study. We investigated:

- **RQ1:** Does reduced noise improve satisfaction, usability, and workload, particularly at preferred walking speeds, compared to the off-the-shelf locomotion controller?
- **RQ2:** How acceptable is our controller's stair-climbing functionality in terms of stability, movement, and logistics from a BLV user perspective?
- **RQ3:** Relative to animal guide dogs, what aspects of the robot require refinement for real-world deployment?

A. Participants

Four BLV participants (ages ≥ 18, visual acuity $\leq 20/200$) were recruited for the study, all experienced guide dog users (9 – 33 years). Three had prior experience with robotic assistive systems. Demographics are summarized in Table II.

B. Procedure

The study comprised four sequential phases:

1) **Walking with primary mobility aid:** Participants first navigated the course (flat path, staircase, ramp) with their guide dogs to familiarize themselves with the environment to perform the same tasks later with the robot (Fig. 6). Afterward, they completed surveys on workload, noise, and usability as listed in Section V-D. We proceeded only after the participant confirmed comfort with the environment.

2) **Robot familiarization and personalization:** Participants were introduced to the robot and rigid harness, then customized for handle length, angle, and walking speed to match their natural gait. Using our locomotion controller, they performed short walking trials to ensure safety and comfort. Unlike prior wizard-of-oz studies [13], we programmed the robot to walk at a fixed velocity to avoid inconsistencies that could arise from human remote control. As our controller maintained stability at normal walking speeds ($\geq 1\,\mathrm{m/s}$), participants freely selected their preferred pace before proceeding to the main evaluation.

3) **Flat terrain locomotion controller evaluation:** We compared the default controller (A) and our controller (B). Participants were told only that they would test “Controller A” and “Controller B”, with order counterbalanced. Each walked at least three trials per controller. After each session, they completed semi-structured interviews and surveys rating noise, satisfaction, and compliance on a 5-point Likert scale [13], along with NASA-TLX workload and SUS usability.

4) **Stair climbing evaluation:** For stair climbing, we used our perception-based quiet locomotion controller to guide each participant through a typical guide dog stair-climbing procedure, as detailed in Section III-B. The robot paused with its front legs on the first step (as depicted in Fig. 6) and awaited a verbal initiation cue (e.g., “forward”). A researcher then triggered a single start command; no further operator input was involved. The robot autonomously climbed the stairs, stopped at the down-ramp, and then descended along a preset straight-line path at the participant's preferred speed.

C. Experiment Environment and Robot Hardware

Trials took place in a 5×5 m lab with flat terrain, a custom staircase, and a ramp. Although dimensions did not fully meet ADA standards due to space and kinematic limits, the setup was designed with input from a BLV participant to ensure safety and accessibility. Floor markings standardized robot initialization, interviews and surveys were conducted with breaks to reduce fatigue, and audio/video were recorded using two smartphones and a GoPro. All tests used the same Unitree Go1 robot (Section IV-A) with a rigid guide-dog handle.

D. Quantitative Metrics

1) Workload: NASA-TLX [31] was used after each session with both the animal guide dog and the robot.
2) Noise: Perceived noise, compliance, and satisfaction were rated on a 5-point Likert scale [13]. For the robot, separate surveys were conducted for flat walking and stair climbing; for animal guide dogs, only once to reduce study duration.
3) Usability: SUS [32] was used after walking on flat terrain using the default locomotion controller, our controller, and climbing stairs using our controller.

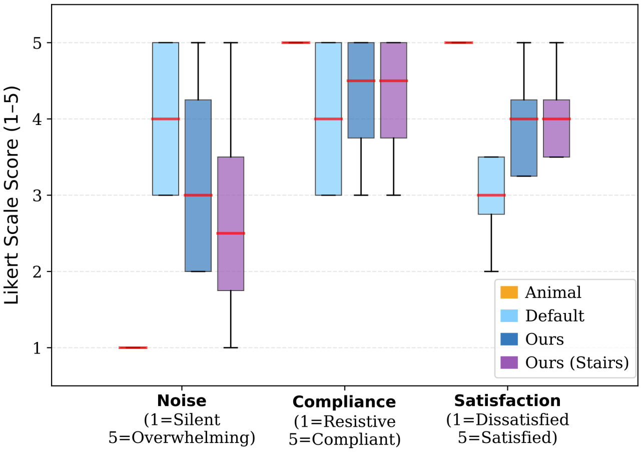


Fig. 7. **Noise, compliance, and satisfaction scores.** Participants rated our controller as quieter and more compliant than the default, while guide dogs (Animal) achieved the highest scores across all categories.

E. *Findings*

1) Smooth and natural gait with reduced noise: All participants reported a noticeable reduction in noise when using our locomotion controller compared to the default controller as shown in Fig. 7. Further, we observed that lower noise levels were associated with higher satisfaction, indicated by an inverse relationship between noise and satisfaction (see Fig. 7).

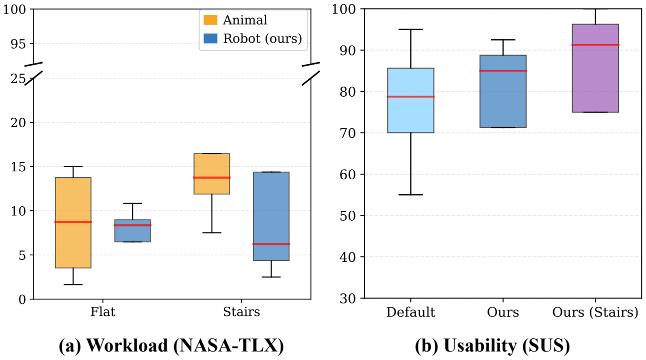
RH03 noted that the default controller would be disruptive in office or library settings, describing it as loud, similar to a small snowblower. Moreover, RH02 emphasized that such noise can be unsafe for a blind person who tries to listen for signals to cross a street. RH01 emphasized that the default controller's gait was uncomfortable: "It's an uncomfortable gait because of the way it kind of jerks up and down much more than the first (ours) gait." RH01 also mentioned that our locomotion controller was much smoother, much less noisy, and much more comfortable, offering a more comfortable walking experience overall:

> "The first robot (ours) gait was much more natural gait. This one is much more of a forced gait with that bbum bbum bbum bbum. Much more robotic, right? The first robot felt much more, much natural. Much more like a natural gait" - **RH01**

2) Comfortable stair climbing: Participants reported that stair climbing with the robot felt manageable and closely resembled their experiences with animal guide dogs. Very low perceived workload remained consistently low (under 20 on the normalized NASA-TLX) although stair climbing can be more challenging than flat terrain walking as RH02 mentioned (see Fig. 8). Although RH03 initially noted feeling nervous ascending stairs with a robot for the first time, he mentioned that he got comfortable at the third try and even expressed a desire to ascend faster.

RH01 and RH04 described that stair climbing with the robot was not difficult, but rather similar to that of stepping up with a guide dog. RH04 added that stair climbing was not difficult since she is already working with a guide dog and the experience was very similar. According to RH02, the distinct stopping points made stair climbing easier, and appreciated this feature since guide dogs, although they are trained to stop, can sometimes make mistakes. As one participant summarized,

> "It was very very similar. I like that it gave me time to step up and then I could give it the command when I was ready. I liked that." - **RH04**



(a) Workload (NASA-TLX)

(b) Usability (SUS)

Fig. 8. **Workload and usability scores.** (a) NASA-TLX shows higher workload on stairs, with our controller reducing demands most notably in this condition. (b) SUS scores indicate improved usability over the default, with particularly high ratings observed even during stair climbing.

VI. CONCLUSION

We developed a noise-reducing locomotion controller for a guide dog robot through a human-centered process of problem identification, system design, and user evaluation. Exploratory studies with guide dog handlers and blindfolded walking revealed that the current quadruped robot controller must be enhanced, especially in terms of noise and vibration suppression. To achieve dog-like smooth and natural locomotion, we reformulated the MPC framework using a real-time SQP framework, enabling high-speed feedback updates while maintaining accurate angular motion dynamics. The integration of this new MPC with WBIC significantly improves balance control, allowing slow stepping and gentle touchdown during walking – even at high walking speeds (e.g., $1.2\ \mathrm{m/s}$). This controller reduces the noise of the robot's walking by $10\ \mathrm{dB}$ compared to the Unitree Go1 robot's default controller, effectively halving the perceived noise level.

We further combined perception with locomotion to support more diverse terrains such as stairs. Throughout the initial exploratory study, we identified that the robot needs to convey the sequence of actions to help the handler recognize and prepare for upcoming terrain height variations. This feature was implemented alongside our perception-based locomotion controller. In human studies with four guide dog handlers, participants noted reduced noise/vibration, improved stair performance, and overall usability.

Beyond these contributions, our work highlights two additional significances: 1) This work is one of the few human-centered developments of guide dog robots, encompassing the complete cycle from problem identification, technology development, and user feedback, and 2) The proposed controller demonstrated significantly improved balance capability over existing methods and has the potential for applications requiring gentle and smooth motion in legged robots.

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