Discrete Control Barrier Functions for Safety-Critical Control of Discrete Systems with Application to Bipedal Robot Navigation

Abstract—In this paper, we extend the concept of control barrier functions, developed initially for continuous time systems, to the discrete-time domain. We demonstrate safety-critical control for nonlinear discrete-time systems with applications to 3D bipedal robot navigation. Particularly, we mathematically analyze two different formulations of control barrier functions, based on their continuous-time counterparts, and demonstrate how these can be applied to discrete-time systems. We show that in general, the resulting formulation is a nonlinear program in contrast to the quadratic program for continuous-time systems. We show that under certain conditions that the nonlinear program can be formulated as a quadratically constrained quadratic program. Furthermore, using the developed concept of discrete control barrier functions, we present a novel control method to address the problem of navigation of a high-dimensional bipedal robot through environments with moving obstacles that present time-varying safety-critical constraints.

I. INTRODUCTION

Barrier Function based control techniques have recently gained success in a wide variety continuous-time systems for safety-critical applications such as precise footstep placement of high degree of freedom bipedal robots [22, 21, 23, 25], adaptive cruise control systems [2], multi-agent systems [29, 4] and quadrotor systems [32, 33, 31]. In these, the problem of stabilization with guaranteed safety is posed as a constrained convex optimization problem, that combines Control Lyapunov and Control Barrier Functions, and solves for an optimal control input that maintains the states of the system with a predefined safety set. In [27], Control Barrier and Control Lyapunov Functions are combined through an analytical framework.

In this paper, we introduce the concept of Control Barrier Functions (CBFs) to discrete-time dynamical systems. Particularly, we analyze the formulation of CBFs presented in [2, 24] and show that these can be applied to directly to discrete-time systems. Interestingly, however, unlike their continuous-time counterparts, we find that the resulting optimization problem is not necessarily convex. For the formulation presented in [24], we show that under certain conditions, the optimization problem is a Quadratically Constrained Quadratic Program (QCQP).

We then apply these concepts to address the challenge of bipedal robot navigation in cluttered and dynamically changing environments such as in indoor urban spaces with moving obstacles, stairs and narrow passages. An example of such a scenario is presented in Fig. 1. Motion planning for humanoid robots has been commonly addressed through planning of footstep placements in constrained environments to handle obstacles, while operating within kinematic limits of the robot. In [19], a vision-based foot placement method is proposed, and implemented on the humanoid robot ASIMO, that searches over a discrete set of actions to avoid obstacles while reaching the goal. A real-time planning algorithm is presented in [3] that utilizes RRTs to search over dense, pre-computed swept volumes to avoid collision with moving 3D obstacles. Other work related to footstep placement planning include [18, 6, 5, 17]. In [8], a Mixed Integer Convex Optimization Program is used to plan footstep placements for bipedal robot walking on uneven terrains with obstacles. A comprehensive review of motion planning for humanoid robots, including whole body motion planning can be found in [14].

In our work, obstacle-free regions are treated as safe sets in the task space. Discrete-time versions of Control Barrier and Control Lyapunov Functions, developed in this paper, are used as high-level planners that issue an optimal heading angle at every to follow a desired path (obtained through path-planning algorithms like A*) while simultaneously keeping the robot in the safe set. A low-level Hybrid Zero Dynamics (HZD) based controller then executes this plan.

The contributions of this paper with respect to prior work are as follows:

- We introduce the concept of Control Barrier Functions [2, 24] for nonlinear discrete-time systems and mathematically show the forward invariance of sets associated with these Barrier Functions (known as Safety Sets).
- Using the concept of discrete-time Control Barrier Functions developed in this paper, we design feedback controllers for high degree-of-freedom bipedal robots to follow a desired path in the task space while avoiding time-varying unsafe regions such as moving obstacles.
- We evaluate our proposed controller through numerical simulations for different desired paths and for static and moving obstacles in the task space.

The rest of the paper is organized as follows. In Section II we introduce the concept of Control Lyapunov Functions (CLFs) and Control Barrier Functions (CBFs) for discrete-time dynamical systems and show the invariance of sets associated with CBFs. We apply the concept of discrete-time CLFs and CBFs to linear systems and show results from numerical simulations. In Section III we apply the concept of Exponential CBFs developed in [24] to discrete-time systems. Again, we apply this concept to linear systems and show results from numerical simulations. In Section IV we develop an event-based controller for a high dimensional bipedal robot for the purpose of following a desired path while simultaneously avoiding obstacles in the task space. Finally, in Section V we conclude by highlighting certain drawbacks of our controller design and indicating directions for future work.

II. LYAPUNOV AND BARRIER FUNCTIONS FOR DISCRETE-TIME SYSTEMS

In this section, we take the concept of Barrier functions developed for continuous-time systems, particularly in [2, 24] and translate it to discrete-time systems given by:

$$x(k + 1) = f(x(k)),$$

where $x(k) \in \mathcal{D} \subset \mathbb{R}^n$ represents the state of the system at time step $k \in \mathbb{Z}^+$ and $f: \mathcal{D} \rightarrow \mathcal{D}$ is a continuous function.

Note: Throughout the rest of this paper, we will represent the state of the system $x(k)$ at time step $k$ as $x_k$.

We show that the same formulation of Barrier Functions developed for continuous-time systems can be applied to discrete-time systems as well. An important observation for discrete-time systems that we will see later is that, unlike continuous-time systems, the resulting Lyapunov and Barrier conditions are not necessarily affine in the control input. Rather, they depend on the nature of the system as well as the nature of the chosen Lyapunov and Barrier Functions themselves. Implementing Control Lyapunov and Control Barrier Functions through optimization may then turn into a potentially non-convex nonlinear program. For the formulation of CBFs in [24], we show that the resulting optimization problem is convex for a class of nonlinear systems and CLFs/CBFs.

A. Lyapunov Functions for Discrete-Time Systems

Consider the nonlinear discrete-time control system,

$$x_{k+1} = f(x_k, u_k),$$

where $u_k \in \mathcal{U} \subset \mathbb{R}^m$ is the control input at time step $k$ and $\mathcal{U}$ is the set of admissible control inputs.

Definition 1. (Discrete-Time Exponentially stabilizing Control Lyapunov Function): A map $V: \mathcal{D} \rightarrow \mathbb{R}$ is an Exponential Control Lyapunov Function for the discrete-time control system (2) if there exists:

1) positive constants $c_1$ and $c_2$ such that

$$c_1\|x_k\|^2 \leq V(x_k) \leq c_2\|x_k\|^2,$$

and

2) a control input $u_k : \mathcal{D} \rightarrow \mathcal{U}$, $\forall x_k \in \mathcal{D}$ and $c_3 > 0$ such that

$$\Delta V(x_k, u_k) + c_3\|x_k\|^2 \leq 0,$$

where,

$$\Delta V(x_k, u_k) := V(x_{k+1}) - V(x_k) = \Delta V_k.$$

Remark 1. The control input $u_k$ renders the origin exponentially stable. See [16] for a comprehensive stability analysis for discrete-time systems.

The concept of Discrete-Time Control Lyapunov Functions has been previously studied in [13] and applied to an automotive engine control problem.

Similar to [9] for continuous-time systems, the CLF condition (4) can be enforced through a constrained optimization program:

$$u_k^* = \arg\min_{u_k} u_k^T u_k$$

$$u_k \in \mathbb{R}^m$$

s.t. $\Delta V(x_k, u_k) + c_3\|x_k\|^2 \leq 0.$

B. Barrier Functions for Discrete-Time Systems

We now show the forward invariance of a set $\mathcal{S}$, know as the Safety Set,

$$\mathcal{S} := \{x(k) \in \mathcal{D} \mid h(x(k)) \geq 0\},$$

$$\partial\mathcal{S} := \{x(k) \in \mathcal{D} \mid h(x(k)) = 0\},$$

for a smooth function $h: \mathbb{R}^n \rightarrow \mathbb{R}$ associated with a Barrier function defined similar to [2] as,
Definition 2. A function $B : \mathcal{S} \rightarrow \mathbb{R}$ is a Barrier Function for the set $\mathcal{S}$ if there exists locally Lipschitz class $\mathcal{K}$ functions $\alpha_1$, $\alpha_2$ and $\alpha_3$ such that
\[
\frac{1}{\alpha_1(h(x_k))} \leq B(x_k) \leq \frac{1}{\alpha_2(h(x_k))},
\]
(8)
\[
\Delta B(x_{k+1}, x_k) = B(x_{k+1}) - B(x_k) \leq \alpha_3(h(x_k)).
\]
(9)
To prove the invariance of the set $\mathcal{S}$ for discrete-time systems, we will need few other results.

Proposition 1. Consider two sequences $\{v_k\}_{k \geq 0}$ and $\{v_k\}_{k \geq 0}$ and their first differences $\{\Delta v_k\}$ and $\{\Delta v_k\}$. If $\Delta u_k \leq \Delta v_k$ and $u_0 \leq v_0$, then $u_k \leq v_k \forall k \geq 0$.

**Proof:**
\[
\Delta v_k = v_{k+1} - v_k
\]
\[
\Rightarrow v_{k+1} = v_k + \Delta v_k
\]
\[
= v_0 + \sum_{i=0}^{k} \Delta v_i
\]
\[
\leq u_0 + \sum_{i=0}^{k} \Delta u_i = u_{k+1}.
\]

Proposition 2. Consider the difference equation
\[
\Delta v_k = \alpha \left( \frac{1}{v_k} \right),
\]
(10)
where $\alpha$ is a class $\mathcal{K}$ function. Then $v_k \geq 0$, $\forall k \in \mathbb{Z}^+$.  

**Proof:** The proof is straightforward and is derived from the fact that $\alpha \left( \frac{1}{v_k} \right) \geq 0$, $\forall v_k \geq 0$.  

Since $v_0 \geq 0$,
\[
\Rightarrow \frac{1}{v_0} \geq 0
\]
\[
\Rightarrow \alpha \left( \frac{1}{v_0} \right) \geq 0
\]
\[
\Rightarrow v_1 = v_0 + \alpha \left( \frac{1}{v_0} \right) \geq v_0
\]
Inductively,
\[
0 \leq v_0 \leq v_1 \leq \cdots \leq v_k, \forall k \in \mathbb{Z}^+.
\]

We are now ready to prove the invariance of the Safety Set $\mathcal{S}$.  

Proposition 3. (Main Result) If there exists a barrier function $B(x_k)$ for the discrete-time system (1), then the set $\mathcal{S}$ is invariant along the trajectories of (1), i.e. if $x_0 \in \mathcal{S}$ then $f(x_k) \in \mathcal{S}$, $\forall k \in \mathbb{Z}^+$.  

**Proof:**
\[
\Delta B(x_{k+1}, x_k) \leq \alpha_3 \circ \alpha_2^{-1} \left( \frac{1}{B(x_k)} \right)
\]
\[
= : \alpha \left( \frac{1}{B(x_k)} \right).
\]
Consider now the difference equation
\[
\Delta B(x_k) = \alpha \left( \frac{1}{B(x_k)} \right),
\]
(11)
with initial condition $B(x_0) \geq 0$. Let the solution be $B(x_k) = \Gamma(x_k)$.  

From Proposition 2,  
\[
\Gamma(x_k) \geq 0, \forall k \in \mathbb{Z}^+ 
\]
and from Proposition 1,  
\[
B(x_k) \leq \Gamma(x_k)
\]
(10)
\[
\Rightarrow \frac{1}{B(x_k)} \geq \frac{1}{\Gamma(x_k)} \geq 0.
\]
(11)
From the left-hand inequality of (8) we have,
\[
\alpha \left( \frac{1}{B(x_k)} \right) \leq h(x_k).
\]
From the inequality in (11),
\[
0 \leq \alpha \left( \frac{1}{B(x_k)} \right) \leq h(x_k)
\]
\[
\Rightarrow B(x_k) \geq 0 \Rightarrow x_k \in \mathcal{S}, \forall k \in \mathbb{Z}^+.
\]

Definition 3. (Discrete-Time Control Barrier Function): A mapping $B : \mathcal{S} \rightarrow \mathbb{R}$ is a Control Barrier Function for the discrete-time control system (2) if there exists:

1) a class $\mathcal{K}$ functions $\alpha_1$ and $\alpha_2$ such that
\[
\frac{1}{\alpha_1(||x_k||_{\mathcal{S}})} \leq B(x_k) \leq \frac{1}{\alpha_2(||x_k||_{\mathcal{S}})},
\]
(12)
and
2) a control input $u_k : \mathcal{S} \rightarrow \mathbb{R}^m$, $\forall x_k \in \mathcal{S}$ and $\gamma > 0$ such that
\[
\Delta B(x_k, u_k) - \gamma B(x_k) \leq 0.
\]
(13)
This essentially means that the control input $u_k$ maintains the Barrier Function $B_k \geq 0, \forall k \in \mathbb{Z}^+$ given that $B_0 \geq 0$.  
In other words, $u_k$ keeps the trajectory $x_k$ of the system within the safe set $\mathcal{S}$, given the initial state $x_0$ lies in the $\mathcal{S}$.  

C. Combining Control Lyapunov and Control Barrier Functions

We pose the problem of combining CLFs and CBFs as a constrained optimization problem (14).  

\[
u_k^* = \arg \min_{u_k} u_k^T u_k + p \cdot d^2
\]
\[
U_k = \begin{bmatrix} u_k \\ d \end{bmatrix} \in \mathbb{R}^{m+1}
\]
\[
s.t. \quad \Delta V(x_k, u_k) + c_3 ||x_k||^2 \leq d
\]
\[
\Delta B(x_k, u_k) - \gamma B(x_k) \leq 0,
\]
\[
u_{min} \leq u_k \leq u_{max}.
\]
Here $d \geq 0$ is a relaxation term that allows the Lyapunov Function to grow when the CLF and CBF constraints are
conflicting. Note that the CBF condition is always satisfied and the trajectory of the system \( x(k) \) always remains within the safe set \( S \). \( u_{\text{min}} \) and \( u_{\text{max}} \) are bounds on the control input. 

Remark 2. Here, we assume that the optimization problem in (14) is always feasible.

D. Application to Linear Systems

Consider the discrete-time linear system,

\[
x_{k+1} = Ax_k + Du_k ,
\]

(15)

with \( x_k \in \mathbb{R}^n \), \( u_k \in \mathbb{R}^m \), \( A \in \mathbb{R}^{n \times n} \), \( D \in \mathbb{R}^{n \times m} \) and the safe set \( S \) defined by the linear function

\[
h(x_k) = Hx_k + F,
\]

(16)

with \( H \in \mathbb{R}^{1 \times n} \) and \( F \in \mathbb{R} \). We choose a quadratic Control Lyapunov Function

\[V_k = x_k^T P x_k,\]

with \( P > 0 \) and symmetric, obtained by solving the discrete-time Lyapunov equation,

\[A^T P A - P = -Q\]

for a positive definite and symmetric matrix \( Q \). The CLF condition (4) is then given by:

\[
\Delta V_k + c_3 \|x_k\|^2 = V_{k+1} - V_k + c_3 x_k^T x_k
\]

\[= x_{k+1}^T P x_{k+1} - x_k^T P x_k + c_3 x_k^T x_k
\]

\[= u_k^T D^T P D u_k + x_k^T (A^T PA - P) x_k + 2 x_k^T A P D u_k + c_3 x_k^T x_k \leq 0\]

Similar to the continuous-time domain [2], we chose the following Control Barrier Function,

\[
B_k = B(x_k) = \frac{1}{h(x_k)} = (H x_k + F)^{-1}.
\]

The CBF condition (13) then becomes

\[
\Delta B_k - \frac{\gamma}{B_k} = B_{k+1} - B_k - \frac{\gamma}{B_k}
\]

\[= - \left( H (Ax_k - x_k + D u_k) \right) \left( H x_k + F \right) - \gamma (H x_k + F)
\]

\[\leq 0\]

Remark 3. Unlike the continuous-time system, the CLF and CBF conditions are no longer affine in the control input \( u_k \) and depend on the choice of \( V_k \) and \( B_k \). This implies that for general nonlinear systems with nonlinear Lyapunov and Barrier Functions, the resulting optimization problem (14) is not necessarily quadratic, or even convex. Moreover, as we have seen, this is also true for linear systems with quadratic Lyapunov functions and linear functions defining the safe set. In Section III we will use a different formulation of the Barrier Function that results in a convex optimization problem for a class of nonlinear systems.

III. DISCRETE TIME EXPONENTIAL CBF

In this section, we show the forward invariance of the safety set using the exponential Control Barrier Function formulation, derived for continuous-time systems in [24], for the discrete-time system (1). Moreover, for the linear system with the safety set defined by a linear function, as described in Section II-D the resulting optimization problem (14) turns into a convex, Quadratically Constrained Quadratic Program (QCQP), unlike a general (and potentially non-convex) nonlinear program with the formulation in [9].

We redefine the definition of the safety set, \( S \) as:

\[S = \{ x_k \in \mathcal{D} \mid B(x_k) \geq 0 \},\]

(17)

where \( B : \mathcal{D} \rightarrow \mathbb{R} \) is called the discrete-time Exponential Barrier Function.

Proposition 4. The set \( S \) is invariant along the trajectories of the discrete-time system (1) if there exists a map \( B : S \rightarrow \mathbb{R} \) such that:

1) \( B_0 \geq 0 \) and,

2) \( \Delta B_k + \gamma B_k \geq 0 \), \( \forall k \in \mathbb{Z}, \gamma \leq 1 \)

Proof: From Proposition 1, \( B_k \geq (1 - \gamma)^k B_0 \geq 0 \), \( \forall k \in \mathbb{Z}^+, \gamma \leq 1 \). This implies that \( x_k \in S \), \( \forall k \in \mathbb{Z}^+ \).

Remark 4. \( B_k \) is always greater than \( (1 - \gamma)^k B_0 \), an exponential function in \( k \), and hence the name Exponential Control Barrier Function.

Definition 4. (Discrete-Time Exponential Control Barrier Function) A map \( B : \mathcal{D} \rightarrow \mathbb{R} \) is a Discrete-Time Exponential Control Barrier Function if:

1) \( B_0 \geq 0 \) and,

2) there exists a control input \( u_k \in \mathbb{R}^m \) such that

\[\Delta B(x_k, u_k) + \gamma B(x_k) \geq 0, \forall k \in \mathbb{Z}^+, \gamma \leq 1.\]

A. Linear System Revisited

In this section, we apply the Discrete-Time Exponentional Barrier Function to the linear system presented in Section II-D. Note that \( B(x_k) \) is equal to \( h(x_k) \) defined in (16). The CBF condition now becomes:

\[
\Delta B_k + \gamma B_k = B_{k+1} + (\gamma - 1) B_k,
\]

\[= H (Ax_k + Du_k) + F + (1 - \gamma)(H x_k + F)
\]

\[= H (A + (1 - \gamma) I)x_k + (2 - \gamma) F + HD u_k \geq 0
\]

Similar to (14), a control input \( u_k \) that ensures the forward invariance of the set \( S \), while driving the state \( x_k \) as close to the origin as possible can be obtained through a QCQP as:

\[
\begin{align*}
u_k^* &= \arg\min_{U_k} u_k^T P_0 u_k, \\
U_k &= \begin{bmatrix} u_k \\ d \end{bmatrix} \in \mathbb{R}^{n+1} \\
s.t. \\
U_k^T P_1 U_k + q_1^T U_k + r_1 &\leq 0 \\
U_k^T P_2 U_k + q_2^T U_k + r_2 &\leq 0,
\end{align*}
\]

(18)
where,
\[
P_0 = \begin{bmatrix} \mathbb{I}_{m \times m} & p \end{bmatrix},
\]
\[
P_1 = \begin{bmatrix} D^T P D & 0 \end{bmatrix},
\]
\[
P_2 = 0_{m \times m},
\]
\[
q_1 = [2x_k^T APD -1]^T,
\]
\[
q_2 = [-HD 0]^T,
\]
\[
r_1 = x_k^T (A^T PA - P + c_3 \mathbb{I}_{n \times n}) x_k,
\]
\[
r_2 = -H (A + (1 - \gamma) I) x_k - (2 - \gamma) F.
\]

**Remark 5.** As we have seen here, the exponential CBF formulation results in a convex optimization problem (particularly a QCQP) for a linear system with quadratic Lyapunov and Barrier functions. Moreover, this is also true for nonlinear, control affine systems with Linear and/or Quadratic Lyapunov and Barrier functions. This can be solved efficiently using MATLAB’s fmincon \[1\] using packages such as CVX \[10\].

**B. Example**

We now present simple examples of the discrete-time CBF-CLF controllers for both linear and nonlinear control affine systems.

Consider the linear system with \( A, D, H \) and \( F \) matrices given by,

\[
A = \begin{bmatrix} 1 & 2 \\ 2 & 2 \end{bmatrix},
\]
\[
B = \begin{bmatrix} 1 & 2 \end{bmatrix}^T,
\]
\[
H = \begin{bmatrix} 1 & 0 \end{bmatrix},
\]
\[
F = -1.5.
\]

Utilizing the discrete-time CBF-CLF controller in \[14\], the trajectory of the system always remains within the safer region (see Fig \[2a\]).

Consider now the discrete-time control affine nonlinear system given by,

\[
\begin{bmatrix} x_{k+1,1} \\ x_{k+1,2} \end{bmatrix} = \begin{bmatrix} \sin(x_{k,1}) + x_{k,1} + 2x_{k,2} + u_k \\ \sin(x_{k,2}) + 2x_{k,1} + 2x_{k,2} + 2u_k \end{bmatrix}.
\]

Linearizing the above nonlinear system yields the linear system in \[19\].

Like in the case of the linear system, the trajectories of the nonlinear system in \[20\] also remain within the safety set (See Fig \[2b\]).

**IV. APPLICATION TO BIPEDAL WALKING**

In this section, we use the concept of Discrete-Time Control Lyapunov (D-CLF) and Barrier Functions (D-CBF) to develop a stride-to-stride controller for a 21 degree of freedom bipedal robot model to follow a given path in the task space, while avoiding static and moving obstacles. We begin by presenting a brief overview of the hybrid zero dynamics framework

(a) Trajectory of the linear system in \[19\].

(b) Trajectory of the nonlinear system in \[20\].
This is when the transition from single support to double support phase occurs. At impact, there is a discrete change in the velocities of the robot, while the configurations remain the same. The post impact states, \((q^-, \dot{q}^-)\) are determined from the impact map \(\Delta (q^-, \dot{q}^-)\), given the pre-impact states, \((q^-, \dot{q}^-)\), assuming a perfectly plastic impact. The hybrid model of the system is then comprised of the continuous time dynamics and the discrete dynamics:

\[
\Sigma : \begin{cases}
    \dot{x} = f(x) + g(x)u, & x \notin S, \\
    x^+ = \Delta(x^-), & x \in S.
\end{cases}
\] (23)

We define the set,

\[
\mathcal{N} := \{(q, \dot{q}) \in TQ \mid \eta_c = \eta_c(q^+), J(q)\dot{q} = 0\},
\]
as the set of states such that the holonomic constraints are satisfied.

### B. Hybrid Zero Dynamics (HZD) Control

#### a) Virtual Constraints:
We define a set of outputs (also referred to as virtual constraints), \(y \in \mathbb{R}^m\), for the control system [23], which consists of velocity regulating and position modulating terms. These are defined as the difference between the actual output, \(y^a(x)\) and desired output, \(y^d(\tau, \alpha)\),

\[
y := y^a(x) - y^d(\tau, \alpha),
\]
where \(\tau(q) \in [0, 1]\) is the gait phasing variable and \(\alpha \in \mathbb{R}^{m \times (b+1)}\) is a set of Bézier Polynomial coefficients of degree \(b\) that parameterize the desired position modulating outputs. An input-output linearizing controller \(\Gamma_{IO}\) drives \(y \to 0\) exponentially [30].

A stable and periodic walking gait can be designed by choosing appropriate values for the parameters, \(\alpha\), that ensure a periodic solution exists for the hybrid system in [23] and the Partial Hybrid Zero Dynamics surface [15] is impact invariant. This can be posed as a nonlinear, constrained optimization problem. Additionally, physical constraints such as joint velocity limits and actuator input bounds, as well as, robot behaviors such as desired step length and walking speed can be incorporated in this optimization problem. Specifically, we utilize the direct collocation framework presented in [15]. Figure 3 shows snapshots of a step of the walking gait obtained using this optimization process.

### C. Stride-to-Stride Controller for Turning

The input-output linearizing controller can be combined with a discrete-time controller based on the Poincaré map, similar to [28, 20], to follow a desired heading angle, \(\phi\). Specifically, we define the Poincaré map \(P : \mathcal{N} \cap \Delta(S) \times B \mapsto \mathcal{N} \cap \Delta(S) \times B\) as:

\[
x_{k+1} := P(x_k, \beta_k),
\] (24)

where \(x_k \in \mathcal{N} \cap \Delta(S) \subset \mathbb{R}^{2n-m+11}\), is the reduced set of states on the post impact surface, \(\Delta(S)\), and which satisfy the holonomic constraints, at the \(k^{th}\) step. \(\beta_k \in B \subset \mathbb{R}^m\) is a set of parameters that modifies the outputs, \(y\), towards the end of a step,

\[
y = y^a(q, \dot{q}) - y^d(\tau, \alpha) - y^b(\tau, \beta_k)
\] (25)

with \(y^b\) defined as,

\[
\begin{cases}
y^b = 0 & \text{if } \tau = 0 \\
y^b = \beta_k & \text{if } \tau = 1 \\
\partial \beta / \partial \tau = 0 & \text{if } \tau \in \{0, 1\}
\end{cases}
\]

The linearized Poincaré map,

\[
\delta x_{k+1} = A \delta x_k + B \delta \beta_k,
\] (26)

can be treated a discrete-time control system, where \(\delta x_k := x_k - x^* + \delta \beta_k = \beta_k - \beta^*\), with \(x^*\) a fixed point of (24) and \(\beta^* = 0_{m \times 1}\). \(A\) and \(B\) are the Jacobians of \(P\) with respect to \(x_r\) and \(\beta\) respectively. A feedback controller \(\Gamma_{\beta} : \mathcal{N} \cap \Delta(S) \to B\),

\[
\delta \beta_k = \Gamma_{\beta} = -K_{\delta} \cdot (x_k - x_d (\Delta \phi_k^d)),
\] (27)

with \(K_{\delta}\) obtained using the DLQR method and \(x_d\) being \(x^*\) with the heading angle replaced by the desired change in heading angle \(\Delta \phi_k^d\), can be developed such that the eigenvalues of \((A - BK_{\delta})\) are within the unit circle.

Fig. 4a shows the path traversed by the robot for different desired heading angles while Fig. 4b shows snapshots of the robot for walking on a circular path, both using the event-based controller [27].

### D. Path Following

Using the above controller, we can follow a desired path by changing the heading angle of the robot from step to step. Consider the desired path can be represented by,

\[
p_y^d = \zeta (p_x),
\] (28)

where \(p_y^d\) is the desired vertical position of the robot, \(p_x\) is the current horizontal position of the robot and \(\zeta : \mathbb{R} \to \mathbb{R}\) is a smooth function.

\textbf{Remark 6.} A desired path for the robot’s position can be computed offline from existing path planning algorithms such as RRTs or A* search.

From (26) and (27), another system can be constructed,

\[
p_{k+1}^t (x_{k+1}) = \bar{P} (p_k^t (x_k), \Delta \phi_k^d),
\] (29)
Function formulation presented in Section III, since this leads to the desired path. Particularly, we use the exponential Barrier obstacles in the task space, while staying as close as possible to the desired path. Hence, we propose to use a discrete-time Control Barrier Function (D-CBF) controller to avoid obstacles.

### E. Obstacle Avoidance

A discrete-time CLF controller can then be developed to follow the given path as:

\[
\Delta \phi_k^* = \arg\min_{\Delta \phi_k} \Delta \phi_k^T \Delta \phi_k \\
\Delta \phi_k \in \mathbb{R} \\
s.t. \quad \Delta V (e_k^y, \Delta \phi_k) + c_3 ||e_k^y||^2 \leq 0, \\
-\Delta \phi^{max} \leq \Delta \phi_k \leq \Delta \phi^{max},
\]

where \( V \) is a candidate Control Lyapunov Function for the discrete-time control system in (30).

Fig. 5 shows the foot-step locations of the robot for different desired paths, \( \zeta \).

**Remark 7.** Here, the change in the heading angle is saturated between \( \pm \Delta \phi^{max} \) to avoid slipping and motor torque saturation.

### E. Obstacle Avoidance

The D-CLF controller can be augmented with a discrete-time Control Barrier Function (D-CBF) controller to avoid obstacles in the task space, while staying as close as possible to the desired path. Particularly, we use the exponential Barrier Function formulation presented in Section III, since this leads to a convex optimization problem (QCQP) for linear/quadratic Barrier and Lyapunov Functions.

In the following examples, we consider the obstacles to be ellipses with semi-major axis \( a \), semi-minor axis \( b \), centered at \((x_0, y_0)\) and the axes of the ellipse aligned with the horizontal and vertical axes of the inertial frame. The Control Barrier Function is then formulated as:

\[
B_k = \left( \frac{p^st_{x,k} - x_0}{a^2} \right)^2 + \left( \frac{p^st_{y,k} - y_0}{b^2} \right)^2 - 1. \quad (33)
\]

Note that \( B_k = 1 \) is quadratic in \( \Delta \phi_k \).

**Remark 8.** Although we only consider ellipses here, the obstacles, in general, maybe any convex shape. Shapes that are described by polynomials of degree higher than two may lead the optimization problem in (34) to be non-convex.

The combined D-CBF-D-CLF controller can be formulated as a QCQP:

\[
\Delta \phi_k^* = \arg\min_{U_k} \Delta \phi_k^T \Delta \phi_k + p \cdot d^2 \\
U_k = \left[ \frac{\Delta \phi_k}{d} \right] \in \mathbb{R}^2 \\
s.t. \quad \Delta V (e_k^y, \Delta \phi_k) + c_3 ||e_k^y||^2 \leq d, \\
\Delta B (p^st_{x,k}, \Delta \phi_k) + \gamma B (p^st_{y,k}) \geq 0, \\
\Delta \phi^{min} \leq \Delta \phi_k \leq \Delta \phi^{max}.
\]

**Remark 9.** The discrete-time CBF controller behaves like a step-to-step planner and gives a minimum change in heading angle \( \Delta \phi_k^* \) at the beginning of each walking step that is required to keep the robot as close as possible to the desired path and simultaneously avoid obstacles. The required change in heading angle \( \Delta \phi_k^* \) is then tracked by the event-based controller in (27). Fig. 6 shows an overview of the complete control system.

**Remark 10.** We note again that the \( d \) term in (34) is required to relax the discrete-time CLF condition (4) so that the Lyapunov Function \( V \) can grow when the the CLF and CBF conditions are conflicting (when the obstacles are on the desired path, our primary goal is to avoid the obstacles rather than to follow the desired path).

In Fig. 7 shows the results of our proposed controller for following a desired path, while avoiding static obstacles on
Fig. 6: Overview of the proposed controller. Dashed lines represent signals in discrete-time.

Fig. 7: Foot-step positions of the robot (in blue) for different desired trajectories (green curve) while avoiding static obstacles (red circle) using the discrete-time CBF-CLF controller.

Remark 11. For the case of moving obstacles, we assume that the robot does not strike any obstacles during the swing phase. This is a reasonable assumption since the step times are in the order of 1s.

Remark 12. For the case of avoiding moving obstacles, traditional path-planning algorithms such as RRTs could be potentially inefficient.

Remark 13. The discrete time CBF-CLF controller can be concatenated with a continuous-time CBF-CLF controller to traverse over more complex terrains such as stepping stones while avoiding obstacles.

V. CONCLUSION

In this paper, we took tools recently developed for safety-critical applications of continuous-time systems and showed mathematically how they can be extended to discrete-time systems. For discrete-time systems, however, using the definition of Barrier Functions in and an additional complexity arises in that the resulting optimization problem to solve for the optimal control input is not necessarily convex. We then used the concept of Exponential Control Barrier Functions and showed that for nonlinear control-affine discrete-time systems, the CLF and CBF conditions are quadratic for quadratic Lyapunov and linear barrier functions and the resulting optimization problem is a convex, a Quadratically Constrained Quadratic Program.

Using this concept of CLFs and CBFs for discrete-time systems, we then developed a stride-to-stride controller for path-following and obstacle avoidance in the task space for a high-dimensional bipedal robot.

In our control design however, we do make certain simplifications and assumptions, which include a linearized models for the Poincaré Map and foot-step placement, which results in a slightly inaccurate estimate of footstep position. This can be addressed by formulating enlarged barriers, equivalent to the amount of uncertainty in estimating the footstep positions. We also assume that we have knowledge about the full state of the robot (such as its position in the inertial frame) and the environment (such as position of obstacles with respect to the robot). In future work, we intend to address this by integrating vision sensors in our control design to estimate the location of obstacles. A primary advantage of bipedal robots is to step over obstacles (of reasonable size) and uneven terrain. In this work, however, we do not consider this. We seek to address this in future by integrating the discrete-time CBF controller with the continuous-time controllers presented to achieve more complex tasks such as walking over discrete footholds or avoiding overhead obstacles. Another important assumption we make is the feasibility of the optimization problem in to guarantee invariance of the safe set.
REFERENCES


