Humanoid Robot's Jumping Capability: a Review

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***Abstract*—This paper presents the progress of completing the second assignment of EE6221. Several humanoid robots would be discussed where their jumping capabilities and jumping mechanism would be mainly focused on. Among those state-of-art humanoids, a novel on-going humanoid robot project lead by the author would be introduced. The significant advantage of such a robot is that it could realize long-distance jet-jumping motions utilizing a ducted-fan propulsion system. This method enables the humanoid robot to jump over 3.5 m (as much as 729% of the robot's leg length) in the simulation platform PyBullet. Later, the challenges and future remarks of such a project would be discussed. Finally, conclusions would be made on how this literature review would have influences on the author's learning in robotics.**

I. Introduction

Recently, various disaster-response humanoid robots were invented with unique control theories or other mechanisms to get over uneven terrains. Traditionally, humanoid robots get over these obstacles by stepping [1] and climbing [2], yet these strategies lack efficiency, especially when operating emergency searching and rescuing missions in real scenarios. It is expected the humanoid robots to accomplish more dynamic performance such as jumping and running motions to handle more complex tasks.

Previous studies had proposed many state-of-art legged robots with vertical jumping ability. Figure 1 shows the leg length and height gain (defined as the center of mass position difference measured from the crouched position to the apex of the jump), for a range of robotic systems. The leg length is comparable to the size of the robot, as we classify them into three categories, miniature robots, multileg robots, and humanoid robots. As the figure indicated, the jumping capability of the robotic systems would not be concomitantly increased with their size. Although the state-of-art miniature robot could jump at multiple times higher than their leg length, even the lasted representative humanoid robot ATLAS [11] could only jump less than half of its height. This indicates how challenging it is to develop a humanoid robot system with high dynamic performance capability. Furthermore, the long jumping capability was not discussed for most of the above humanoid robots. Meanwhile, the landing impact should be considered for the humanoid robots in many cases which may increase the possibility of the collapse of the terrain.

Table I shows the detailed parameters of some robots mentioned in Fig. 1. The vertical jumping agility measures the average vertical speed, and defined as:

$$\text{Vertical jumping agility } (m/s) = \frac{Height}{Period} = \frac{Height}{t_{stance} + t_{apogee}}$$

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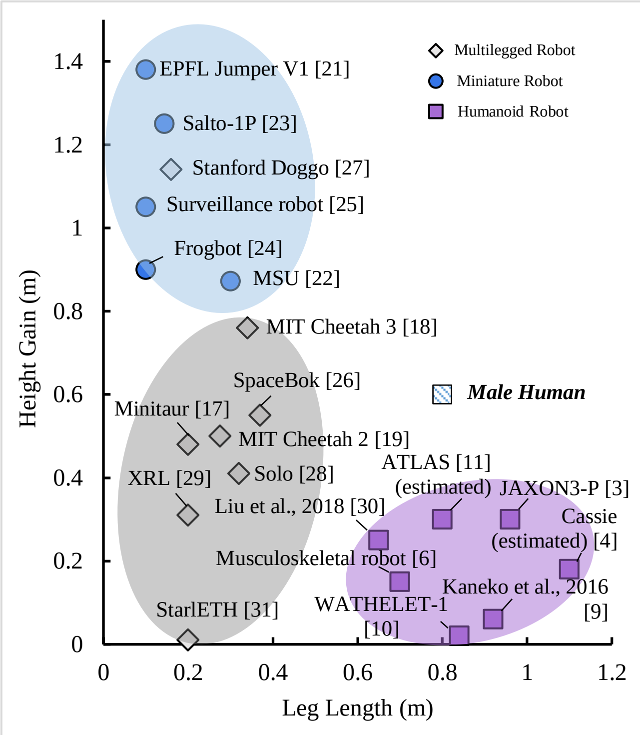


Fig. 1: Height gain and leg length for several robotic systems

As the table indicates, former studies on jumping humanoid robots had not realized jumping high (more than 30 cm) and jumping far (more than 100 cm) simultaneously in a single jump. Such capability is critical for emergency operations in the post-disaster environment. In this case, designing a humanoid robot featured with mentioned capability is innovative and of vital importance.

In relation to achieving good jumping performance on humanoid robots, many methods have been proposed. One approach is weight-saving. Kojima et al. proposed a high stiffness optimized mechanical structures design, and the effectiveness has been proven by a prototype robot JAXON3-P dynamically jumping 300 mm in height [3]. Compared with the previous JAXON series, this new structural optimization successfully reducing about 62 percent of the frame weight. Deigned with concentrated mass at the pelvis, Cassie [4] has lightweight legs with leaf springs and a closed kinematic chain mechanism that could jump about 180 mm in height. Another approach is enhancing power where pneumatic artificial muscles (PAM) actuators were introduced [5][6]. Taking advantage of the properties of PAM, in follow-up studies as in [7][8][9], the latest musculoskeletal humanoid could accomplish sequential jumping-stepping motions. Otani et al. [10] proposed a jump method by combining active joint driving with spring behavior in an actuator to achieve countermovement jumping motion. As a representative humanoid robot, ATLAS [11] can jump high and execute complex tasks driven by hydraulic actuators.

TABLE I

COMPARISON EXISTING ROBOTS WITH THE JUMPING ABILITY

Robotic Systems	Mass [kg]	Size [cm]	DoF (Leg)	Jumping height [cm]	Jumping distance [cm]	Vertical Jumping Agility (m/s)	Actuation
EPFL Jumper V1	0.00698	5	N/A	138	79	0.34	electric motors
Salto-1P	0.098	15	N/A	125	200	1.83	electric motors
Surveillance robot	0.15	12.2	N/A	105	60	×	electric motors
MSU	0.0235	6.5	N/A	87.2	89.8	×	electric motors
Stanford Doggo	4.8	42	8	114	0	2.23	electric motors
MIT Cheetah 2	33	×	12	50	×	1.11	electric motors
MIT Cheetah 3	45	20	12	76	×	×	electric motors
SpaceBok	20	50	4	55	×	0.15	electric motors, springs
JAXON3-P	70	170	12	30	0	0.6	electric motors
Cassie	31	115	6	18	< leg length	×	electric motors
New ATLAS	80	150	12	30 (estimated*)	< 100 (estimated*)	×	hydraulic actuators
This work	15	90	12	40	350	0.2	motors & ducted-fans

× Data not available from the reference
* Estimated through the video published by Boston Dynamics at https://www.youtube.com/watch?v=_sBBaNYex3E&ab_channel=BostonDynamics

Besides, there is a possibility of utilizing aerodynamic lift to improve the dynamic performance of the traditional robot. Zhao et al. developed a dragon-like aerial robot based on duct fans. The robot can transform into the air to fly across a narrow space [12]. iCub [13] robot from IIT had complete flying simulation focused on control strategy and stabilization. In our previous work [14], a jet-powered humanoid robot, Jet-HR1 was innovatively proposed with a ducted-fan installed on each of its feet. By keeping a quasistatic balance, the robot could step over a ditch with a span of 450mm (as much as 97% of the robot's leg) in 3D stepping. Recently, with further optimization, the robot could perform extreme posture to stepping over a gap at about 147% of the robot's leg length, this work would be published later.

To improve robot behavior and understand the jumping mechanism, several motion strategies were introduced. However, very few of these strategies considered absorbing landing impact. In the later work on JAXON3-P [15], researchers analyzed the relationships between joints stiffness, reflected inertia, and actuator mass and proposed a force control method to maintain dynamic balance when performing motions. For the musculoskeletal humanoid robot, one posture control with joint angle controller was designed by Sulistyoutomo et, al. [7]. These series of pneumatic and SEA robots absorb impact forces by their intrinsic joint elasticity. To minimize the damage to both the robot and the post-disaster ground, when design electric-powered robots, the impact, especially the heavy impact caused by motions like jumping, should be considered.

The main objective of this study is to introduce an ongoing humanoid robot project lead by the author. This robot could realize jet-jumping motions powered by both electric actuators and a ducted-fan propulsion system.

The paper is organized as follows. In Section II, we described the main mechanical design and specification of the robot. Then, we present the simulation based on the control theory to achieve the jet-jumping motion. Section III presents the discussion of this ongoing project, including the challenging points and future remarks. Finally, in section IV, the conclusion would be made based on the review of the latest research on humanoids' jumping motions. Comments on how these researches exert far-reaching influences on the author would be made as well.

II. ONE BEST SOLUTION: JET-HR2

Focused on accomplishing jumping motions, we selected this ongoing project as the best solution based on the critical criteria of performances like jumping height/distance in a single jump.

A. *Specifications of Jet-HR2*

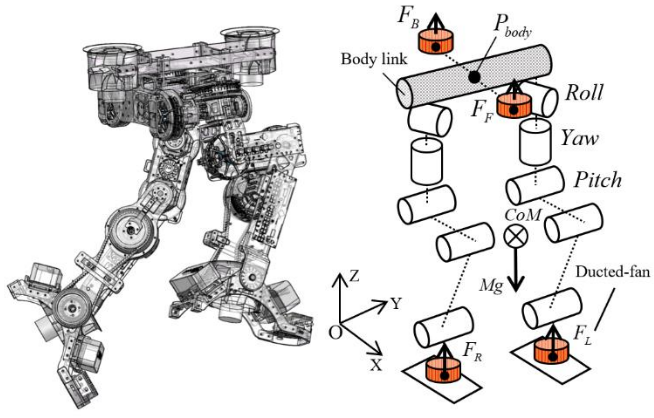
Several general design indexes should be primarily determined to further achieve a sophisticated mechanical system with appreciate structural dynamic characteristics. For humanoid robots capable of accomplishing high and dynamic jumping motions, a lightweight design, powerful actuators, high executive precision, and large workspace should be considered as design objectives. Following these objectives, we designed the prototype robot Jet-HR2.

TABLE II

MAIN SPECIFICATION OF JET-HR2

Component	Description
Weight	15 kg
Height	700 mm
Degrees of freedom	10
Length of leg	480 mm
Ducted fan	90 mm, 48 V, 488 g
	Max thrust 55 N @ 90 A
Joint motor	T-Motor Co. Ltd. U8-Lite KV150, 24 V, 1.83 Nm; A-80-9, 24V, 18 Nm
Reducer	Harmonics Drive
	CSF-11-50-1U-CC-SP, 50:1
Battery of motor	24 V, 4200 mAh
IMU (Six-axis)	ASENSING CO. Ltd.
	INS550

As indicated in Table II, Jet-HR2 is 700 mm high and has a mass of 15 kg, including batteries. The length of the robot's leg was defined from the roll joint of the hip joint to the feet



(a) (b)

Fig. 2: (a) The prototype robot Jet-HR2, (b) The ducted-fan configurations

and is 480 mm. Different from our previous prototype humanoid robot Jet-HR1 [14], Jet-HR2 has only 10 Degrees of Freedom (DoFs), where the hip joints are composed with hip joint (Yaw), (Roll), (Pitch), consecutively. For actuation, Jet-HR2 has two different electric actuators to satisfy the joint torque and speed requirements for dynamic motions. These features enable Jet-HR2 to has a large workspace and a lightweight mass to perform challenging tasks.

Furthermore, according to the robot's weight, a lightweight metal ducted fan JP90 (Shenzhen JP. Co., Ltd.) was chosen. Each ducted fan weighs 488g while could provide a maximum of 55 N at 48V DC power. As indicated in the ducted-fan configurations of the robot (Fig. 2), the robot has four ducted fans with two on the waist and two on each of the ankles.

B. Modular Joint Design

Jet-HR2 uses modular joints (Fig. 3) in hip and knee degrees of freedom.

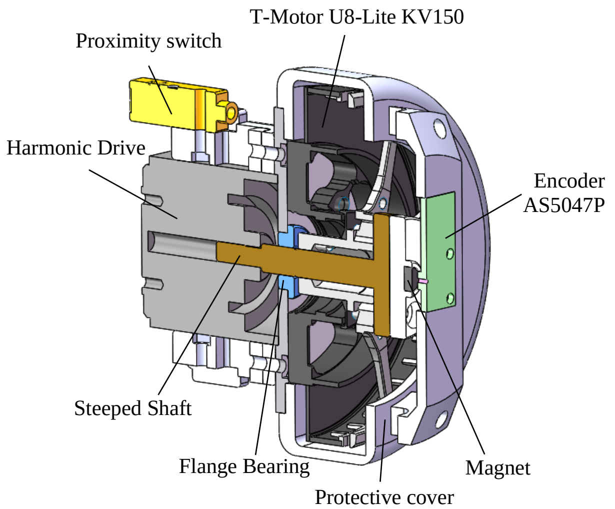


Fig. 3: The modular joint design used in Jet-HR2. Motor, Harmonic Drive and multi-sensors are integrated.

The utilization of modular joints on robots has several advantages including easier repairs, modification, and simplifies design [16]. The coordination of high torque density brushless motor and a Harmonic Drive could achieve a high output torque, accurate force/torque control precision, and remains back-drivable as most of the state-of-art legged robots. The modular joint in Jet-HR2 is composed of a brushless motor (T-Motor U8-Lite KV150) and a Harmonic Drive (CSF-11-50-1U-CC-SP). Here we chose a high transmission ratio of 50, which the maximum effective torque can reach 30 Nm. Furthermore, we integrated an absolute magnetic rotary encoder (AS5047P) placed off-axis on the protective cover to communicate with the motor controller ODrive (ODrive Robotics, Richmond, CA) based on CAN-Bus. For initial position correction, the proximity switch is settled at the Harmonic Drive set printed in ABS plastic materials. Besides high torque density and high control precision, the modular joint is compact and featured weighs 604g.

C. Leg Design

To reduce the leg inertia which is highly related to the placement of the knee actuators, many optimizations had made by previous researches such as Cassie [4], Minitaur [17], and MIT Cheetah series [18][19]. These robots have the knee joint placed close to the hip joint to put the center of mass (CoM) on the higher part of the robot as much as possible. Similarly, we optimized the leg design on Jet-HR2 by aggregating the hip joint (Pitch) and the knee joint on the same carbon frame as integrated.

Fig. 4 shows the mechanical design of the robot's thigh part. The three-DoFs hip joints are allocated separately, with the hip joint (Roll) mounted on the waist. The hip joint (Yaw) is located between the two carbon frames of the pelvis. In addition to the purpose of reducing leg inertia, another consideration of the thigh design is the workspace where the Roll-Yaw-Pitch configuration enables the robot to have a maximum range of motion. The hip joint (Roll) could rotate + 0 ~ 90°, the hip joint (Yaw) could rotate + 0 ~ 135°, the hip joint (Pitch) ± 90°, and the knee joint ± 110°. This range of workspace could allow the robot to use its whole leg length in dynamic motions like stepping over a large ditch in 2D gaits [20], which contributes to enhancing the locomotion performance.

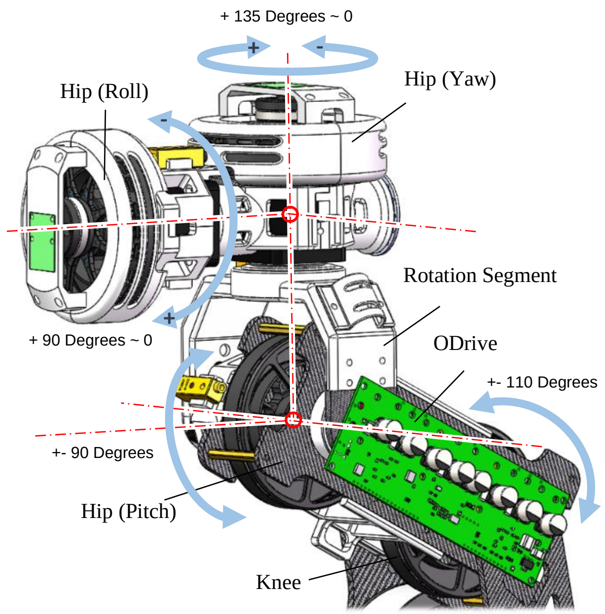
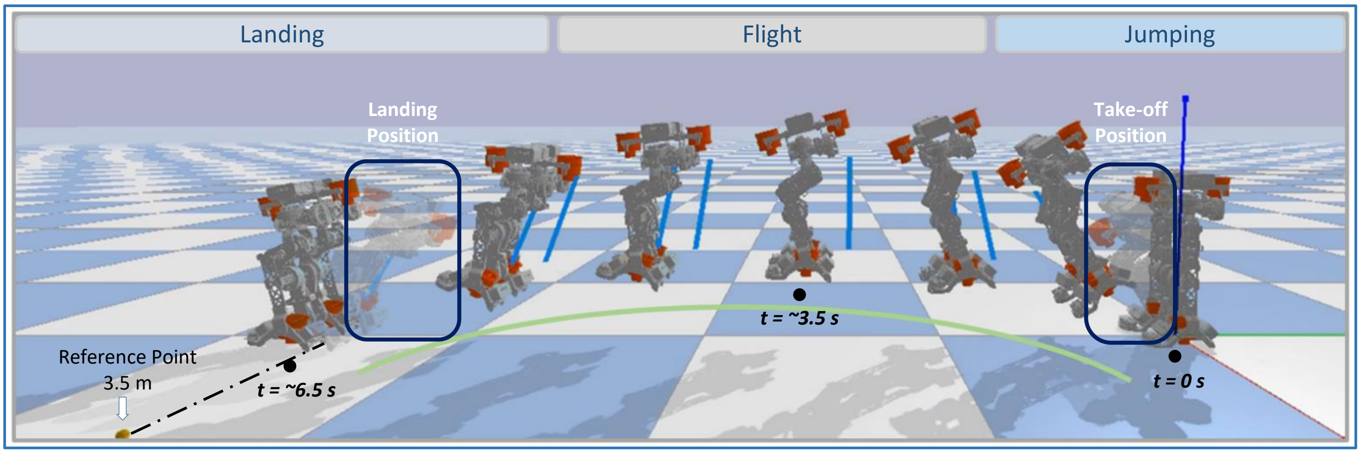
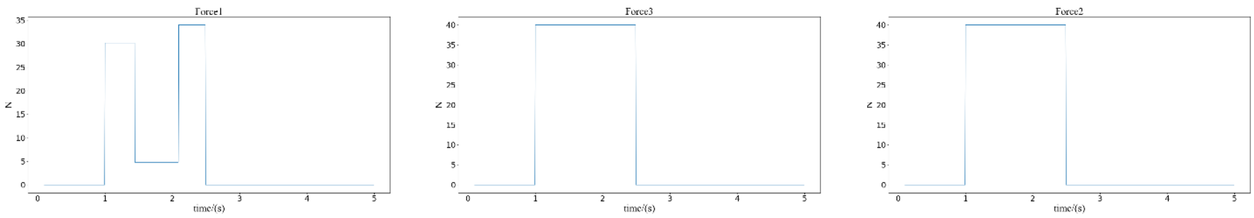


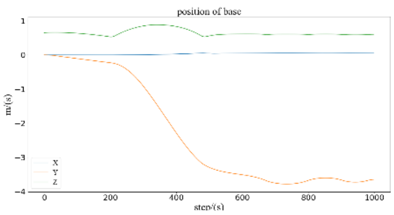
Fig. 4: The design of a Jet-HR2 Leg (right).



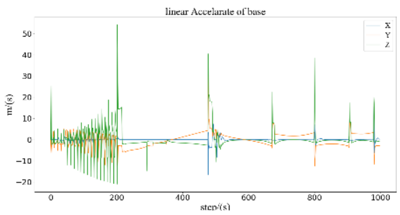
(a) Jumping simulation



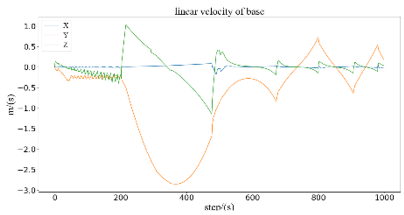
(b) Thrust of Fans



(c) Position of base



(d) Linear acceleration



(e) Linear velocity

Fig. 5: Simulation results: snapshot of the jumping of Jet-HR2

The actuators on the shank are different from the thigh parts mentioned above. Here we use the integrated actuator A80-9 motor (T-Motor Co. Ltd.) to satisfy the higher speed need for jumping motions. This motor We evaluated the velocity and torque on a physical simulation platform PyBullet to determine the appropriate transmission ratio for the ankle joints. As shown in Fig. 5, torque is transmitted to the robot's feet through a 28:50 belt drive. The belt transmission further contributes to reducing the leg inertia and helps to improve the stiffness.

For the feet design, we integrated the ducted-fan on the ankle joints, and the fan controller is mounted on it. More details would be provided in future publications.

D. Simulation

Based on the above mechanical design focusing on jumping motions, we evaluated the jumping performance of the robot in simulations using a simple PID controller. The purpose of the simulation is to verify the potential dynamic performance of the mechanical design of the robot.

The simulation starts from an initial standing posture. Jumping was initiated as knee flexion reached a certain position. Given a desired time, at the moment of jumping, we active the ducted-fans, then change the thrust of the propulsion force according to the robot's flying posture. During the phase from initializing posture to the peak of the flight, the robot's feet would stretch. Then in the landing phase, the robot would bend to certain degrees to absorb the landing impact. The jumping trajectory was shown in Fig. 5 (a). Fig. 5 (b) shows the thrust change of the ducted-fans, in this jumping simulation we only employed three fans (two on the ankle, one on the front of the waist). Since the real thrust variation curve is hard to estimate, in this simulation we idealized and assume the thrust can change instantaneous. Fig. 5 (c) (d) and (e) show the position, linear acceleration, and linear velocity of base respectively.

As the simulation results indicated, the jumping distance of the robot could reach at 3.5 m which is farther than most of the recent humanoid robot researches.

III. Disccusion

Although in the simulation the prototype robot could jump at 3.5 m far, this dynamic motion should be applied to real experiment to verify. However, this progress would bring many potential challenges especially the error or what called reality gap between the simulation and real experiment.

This reality gap contains the centroid error between simulation model and prototype robot. Besides, in the simulation we neglected the aerodynamics effects and the ducted-fan's own dynamics, as well as the ducted-fans' thrust on the terrain. We made assumptions in the simulation that the thrust of the ducted-fans could immediately reach the maximum power, yet this may not be real in the real scenarios. These all factors should be addressed from the simulation to the real experiments.

Besides these challenges, there is still a potential of accomplishing more versatile motions based on this robotic system. More specifically, in the jumping simulation, we only utilized three of the ducted-fans for a very short time. If we operate the ducted-fans for a longer time with an aerial manipulation control strategy, the robot may capable of completing complex flying motions. And this is also one of the subjects of future work.

To address the challenging points in the reality gap problem, the main approach is to design a robust controller, especially by injecting noise in the simulations to enhance the robot's stability. Then several centroid error compensation methods should be applied to calculate the real center of mass (CoM) of the robot for accurate controlling. Also, more advanced algorithms like deep reinforcement learning (RL) could be applied to find the optimum jumping trajectory when giving certain conditions.

IV. Conclusion

This paper presents the second assignment of EE6221. An ongoing project was introduced to have the potential of having the best jumping capability among other state-of-art humanoid robotic systems, as shown in Fig. 6. Part of the mechanical as well as the simulation was presented. The result of the simulation shows that the robot could accomplish jet-jumping motions with a jumping distance of 3.5 m.

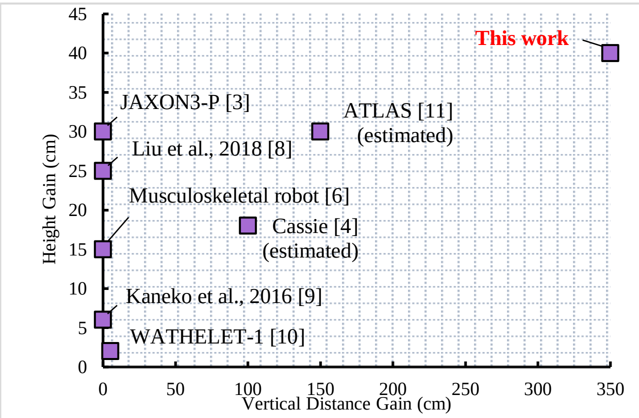


Fig. 6: Comparison of state-of-art humanoid robotic systems

The challenging points include how to narrow the reality gap between simulation and real prototype experiments. Also, the robotic system has the potential of accomplishing more versatile motions using the ducted-fan propulsion system.

Regarding the reflection of this assignment, after literature review, it can be concluded the robotics research is an interdisciplinary field where mechanical and algorithms are both indispensables. After the mechanical design and its verification, the algorithms should be designed to maximum the robot's dynamic performance which is difficult.

Upon graduating, in addition to learning innovations from more perspectives through systematic study and research, I hope to deepen my appreciation of robotics through Ph.D. study.

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