Heading Control for Quadruped Stair Climbing based on PD Controller for the KRSRI Competition

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Abstract – **Quadruped, a robot that resembles four-legged animals, is developed for many purposes, such as surveillance and rescue. Such a caveat requires the robot to have the capability to overcome various terrain and obstacles. When moving across such a landscape, it is essential to maintain the robot's orientation steadily. Inclined terrains such as stairs have posed another challenge to the control strategy as the robot is unstable while climbing. Therefore, the contribution of this work is to address the need for heading control because of the relatively longer stairs used for the current competition compared to the past. The proposed control system simultaneously maintains the heading while keeping the body stable. The inertial measurement unit sensor carried by the robot would provide the pose needed for heading control calculations. The robot's heading becomes the base for the PD controller calculation. The final pose that stabilizes the robot while tackling heading error is a combination of correction from the PD controller and the stabilization part of the control strategy. Then, the leg servo angle determination deployed the inverse kinematics calculation from the suitable robot pose. The proposed method enabled the designed robot to maintain its heading with a 4.4-degree margin of error and stabilize the body. The quadruped also completes the stair climbing at the shortest time of 20 seconds with a speed of up to 5.5 centimeters per second.**

*Keywords: Heading control, inverse kinematic, PD controller, quadruped robot*

I. INTRODUCTION

A quadruped robot is a type of robot useful for various purposes. Legged robots, in general, have an advantage when navigating rough terrain. Therefore, those legged robots are the best choice for surveillance, search, and rescue missions. Legged robots have been the selected theme for the KRSRI (Indonesian Search and Rescue Robot Contest), formerly KRPAI (Indonesian Fire Extinguisher Robot Contest), and the author has seen many improvements in the contest rules year by year. In 2023, there have been significant changes to the terrain used for the contest that urges the authors to redevelop the control strategies for the designed quadruped.

Three substantial changes newly introduced in the 2023 contest will create difficulty for robot mobility throughout the competition: the introduction of rocky terrain, cracked terrain that resembles earthquake aftermath, and longer stairs to climb. As opposed to the 2020 rule, which has been researched by our former research team [1], the current contest requires the robot to navigate a more elongated staircase with a total length of 1 meter in its slope. Furthermore, the stairs are more inclined with an inclination of 30 degrees as opposed to the former 20 degrees, as seen in Figure 1. Another noticeable feature is the narrower tread from the former 5 cm to 3.6 cm, and the total traversing length enlengthened five-fold from 20cm to 100cm. This fact requires a robot that is both stable and consistent in its direction.

Therefore, in the current article, the authors propose a heading control strategy for quadrupeds climbing an elongated staircase in the case of the 2023 KRSRI stair contest rule for result validation. This work introduces heading control on the stair climbing control problem. The previous work only addresses the overall robot balance during the stair-climbing process. The robot deviates from its heading at an accumulated rate of 1.3 degrees per second on a flat surface. This fact presents an issue when climbing a lengthy stair, in which this accumulated error will lead to unfitting poses for stair climbing that could lead to accidents such as slipping during the climbing process. The PD controller becomes the base to maintain the robot heading on the objective. The calculation of heading control is then aggregated with the robot balancing strategy based on Fuzzy logic to give the stable footing within the desired heading target.
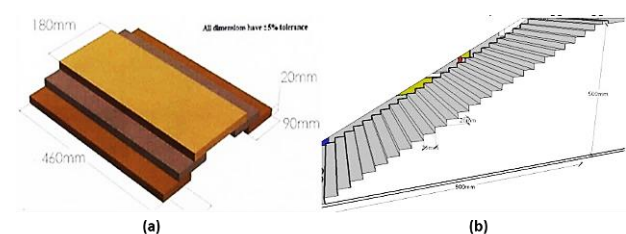
Figure 1. KRSRI rule for stairs on (a) 2020 (b) 2023

Engineers have discovered numerous ideas and ways to achieve stability running on four-legged robots. This part of the article describes the prior work linked to this research, which is relevant to the control and stabilization of quadruped robots. Similar to the study [2] that used

fuzzy algorithms to create quadruped robots that could climb hills and stairs.

In addition, the study paper [3] on quadrupeds, or four-legged robots, running under tilted, balanced settings using the IMU GY-25 gyro sensor in the body's middle. Then, in the study work [4], how to use a series of trot diagrams with PID control to stabilize the movement of quadruped robots. Furthermore, control techniques are employed to keep the balance and motion of the vehicles in the study work [5,6] that balances one-wheeled robots utilizing PID methods. The PD controller had an advantage over the PID controller because the error in heading is an accumulation of wrong leg placement, which has a lower order of motion. Therefore, the PD controller is sufficient for the purpose and would give a faster processing speed from the PID implementation, which is desirable for the competitive scene.

The legged robot's kinematic or structure design influenced the movement heavily [7, 8]. Following the robot's kinematics, the specific robot's walking trajectory may be developed [9, 10]. Production of robot leg moving patterns uses the kinematic inverse approach from the desired coordinate points [11]. There have been reports of four-legged robots moving around in a three-dimensional environment populated by simple geometrical forms [12]. By exploiting the location of its yaw, pitch, and roll in its later research [13], it is demonstrated that quadruped robots can move adaptively against diverse shocks while traversing uneven terrain.

The topic of quadruped stair climbing is recent research in [14] and [15] with stairs of one to three steps. Quadruped can also traverse a lengthy staircase with various performances [16]. All of those studies used a different configuration of legs as opposed to this research. Therefore, adopting the result from those researches needs a slight adjustment in the kinematics as in [17] deployed by the author. More importantly, the inspiration for heading control implemented generally on uneven terrain came from [18]. The article addresses the yaw control for a hexapod on that rough terrain. The authors adopted the principle of gait planning and implemented it in quadruped gait planning. Then, the newly founded gait trajectory planning merges with the existing control plan for stair climbing developed by the authors.

## II. METHODOLOGY

A. Quadruped Kinematics

The quadruped robot developed in this article by the author's team has a spider-like leg configuration. The leg has three joints to which the servo motor is attached. These three joints divide the robot's legs into three parts, called the coxa, femur, and tibia, consecutively, according to the location. The coxa is moved by servo 1, the femur by servo 2, and the tibia by servo 3. Respectively, refer to the angles formed by each servo as θ_1, θ_2, and θ_3. Figure 2 shows the configuration of the quadruped leg developed by the author.
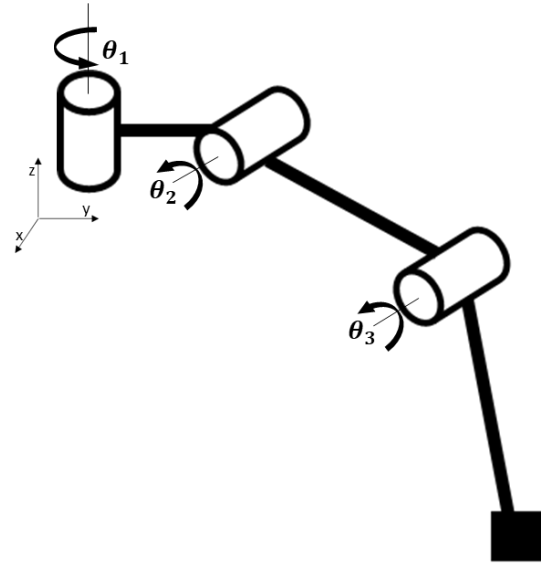
Figure 2. Design of quadruped leg

Acrylic and 3D printing were the materials chosen for the robot's head. That light-weighted material makes the robot head as light as possible. Additionally, fiber PCB is used in the robot body to make it sturdy and lightweight. Next, the components for the quadruped body are 3D-printed parts with PLA and aluminum plates. The 3D printer creates the coxa and tibia portion and the aluminum plate for the femur section. The tibia has an additional 1 cm length from the previous study [1] to ensure that the foot can reach the steps as efficiently as possible. The STM32F4 microcontroller chip, voltage regulator, servo driver, and MPU6050 sensor are parts of the mainboard's hardware architecture. The midpoint or reference should be as close to the mechanical structure of the robot's center as possible, increasing the accuracy of the produced data.

In this investigation, an ARM Cortex-M4 microcontroller with STM32F407VG code produced by STMicroelectronics and an MPU6050 IMU (Inertia Measurement Unit) sensor linked to an Arduino board as a slave controller served as the microcontroller. The STM32F407VG microcontroller can execute flash memory at up to 168 MHz and contains 1 Mbyte of flash memory. Another benefit of this microcontroller is the floating-point units and DSP instruction functions. Those two properties make the microcontroller qualify as a suitable controller for robotics applications [13]. Then, utilizing accelerometers and gyroscopes bundled into one Arduino-compatible module with 12C connectivity, the MPU6050 sensor is used to monitor speed, direction, and gravity force. In obtaining a better reading, the data from MPU6050 must be filtered [11]. It generates acceleration and angular speed data for Yaw (Z-axis), Pitch (X-axis), and Roll (Y-axis). Figure 3 shows the completed robot for this experimentation from the top view (a) and side view (b).
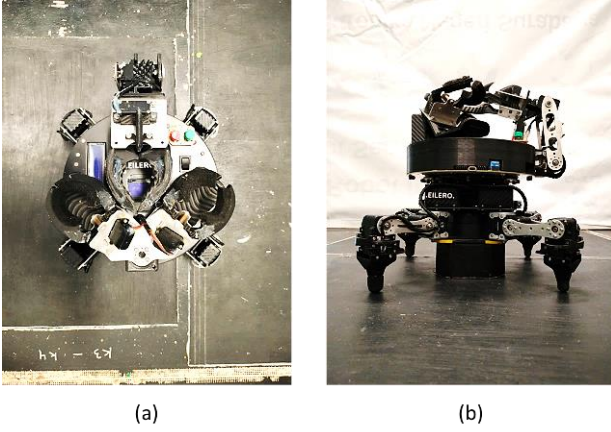
Figure 3. Quadruped designed for the experimentation: (a) top view, (b) side view

A UART circuit is the means of communication between the slave and the master, which is slower than parallel since it theoretically transfers data bit by bit. Occasionally, packets are lost when data changes too quickly, especially in the stair climbing case when the robot brings on a jolt as it ascends the stairs. As a result, creating more accurate output data requires a filter called Moving Window Average (MWA) and allows for real-time data transmission.

The forward kinematics of the robot determines the toe or leg extension based on input to each servo. Meanwhile, inverse kinematics analysis determines the suitable angle of the robot's legs. The formula of forward kinematics in one robot leg is as follows:

$$l_E = \sqrt{l_2^2 + l_3^2 - 2l_2 l_3 cos\theta_3} \qquad (1)$$

$$\theta_E = \theta_2 + \cos^{-1} \frac{l_2^2 + l_E^2 - l_3^2}{2l_2 l_E} \qquad (2)$$

$$z_E = z_0 + l_E cos\theta_E \qquad (3)$$

$$v_E = \sqrt{l_E^2 - z_E^2} \qquad (4)$$

The coordinate (x_0, y_0, z_0) on the leg represents the position of the connected portion to the robot body. The coordinate (x_E, y_E, z_E) represents the position of the tip of the leg. The variables l_1, l_2, l_3 represent the length of the coxa, tibia, and femur. The formulation for the inverse kinematics of the robot is as follows:

$$v_E = \sqrt{x_E^2 + y_E^2} - l_1 \qquad (5)$$

$$\theta_1 = \tan^{-1} \frac{y_E}{x_E} \qquad (6)$$

$$\theta_3 = \cos^{-1} \frac{l_2^2 + l_3^2 - l_E^2}{2l_2 l_3} \qquad (7)$$

$$\theta_2 = \tan^{-1} \frac{z_E}{v_E} - \cos^{-1} \frac{l_2^2 + l_E^2 - l_3^2}{2l_2 l_E} \qquad (8)$$

To achieve the desired position of each leg, move each servo on the legs according to the desired angle. Quadruped movement results from the revolution of the

quadruped legs according to a trajectory that forms dynamics. The movement patterns designed for these quadrupeds mimic the gait of a spider in its walk, trot, and strides. The reaction force from the floor influences the dynamics of the robot, possibly making a deviation from the planned gait, and the formulation is:

$$m(\ddot{\boldsymbol{p}}_{gl} + \boldsymbol{g}) = \Sigma \, \boldsymbol{F}_{gr,i} \qquad (9)$$

$$\boldsymbol{I}_{quad}\dot{\omega}_b = \Sigma \, (\boldsymbol{p}_{leg,i} - \boldsymbol{p}_{gl}) \times \boldsymbol{F}_{gr,i} \qquad (10)$$

B. Heading Control Method using the PD controller

The control technique proposed in this paper is a PD controller to achieve the desired facing direction. Facing error is the basis for determining robot movement. Denote the actual facing or heading direction by the symbol ψ, while the intended facing direction is ψ_d. Denote the proportional and derivative controller constants by K_p and K_d, respectively. The control formulation given to the system is as follows:

$$G = K_p(\psi - \psi_d) + K_d(\dot{\psi} - \dot{\psi}_d) \qquad (11)$$

The usual movement produced by the robot's walking gait is a straight line. Compensating a deviation from the direction it is facing, the trajectory of each leg must form a curve so it turns around as the direction of movement. The correction of the foot position is in proportion to the magnitude of the compensation value G.

The curve of movement forms an incidental center of curvature in the opposite direction to the heading error. Denote the distance from the center of the curve to the robot center by R. The initial robot plan sets the value of R, which relates to the steepness of the correcting action. Figure 4 shows the desired curve-like movement that would correct the robot heading accordingly. Let L_G be a variable dependent on G. The length of the AEP-PEP of the legs on the inner curve is reduced proportionally to L_G while the legs on the outer curve are added in equal proportions, namely:

$$L_{in} = L - L_G \qquad (12)$$

$$L_{out} = L + L_G \qquad (13)$$
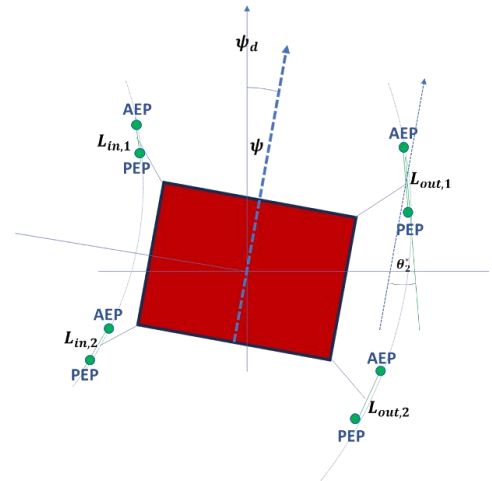
Figure 4. The curvature of turning gait

The tilting angle of the AEP-PEP movement also needs to be corrected so that the robot's movement follows the shape of the curve. As examined in Figure 4, the front legs need to be moved against the direction of the heading error, while the back legs follow the heading error. The amount of tilt correction angle has the opposite characteristic of the AEP-PEP length. The inner curve legs should have a steeper correction or a sizeable tilt from the outer curve legs. Denote the correction angle of the inner legs by θ_1^* and the rest by θ_2^*. Consider W as the distance between the front and back legs, while L is the width of the robot. The correction angle materializes from the calculation according to the following formula:

$$\theta_1^* = \tan^{-1} \frac{W}{2R-L} \qquad (14)$$

$$\theta_2^* = \tan^{-1} \frac{W}{2R+L} \qquad (15)$$

The implementation of heading control follows the block diagram depicted in Figure 5. The heading or yaw angle obtained from IMU measurement admitted the control system. The controller calculates the appropriate control signal or correction factors by equation (11), resulting in the correction factor G. Then, the balancing system from previous research [1] will adjust the position of the leg into suitable leg positions that also maintain the global balance of the robot. The inverse kinematics formulated in equations (6), (7), and (8) convert the leg positions into servo angles. The appropriate servo angle becomes the servo command for the desired poses.
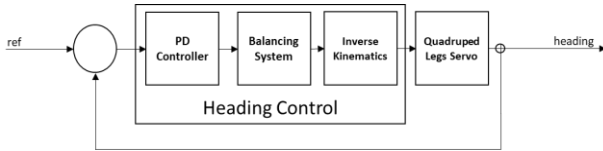

Figure 5. Block diagram of the heading control system

III. RESULTS AND DISCUSSION

A. *Heading Control Performance*

Before the implementation of stair climbing, the author confirms the heading control by examining the performance of the heading control on a flat surface without climbing. Formerly, the authors intended to compare the run of stair climbing with the proposed method against the former research [1], which does not incorporate heading control. However, it raises a concern that if the deviation on the heading angle is too big, the robot would slip and have an accident. Therefore, the author confirmed it first by comparing a run with and without the heading control on a flat surface. The result shown in Figure 6 alters the author's decision to compare the proposed method directly to the stair climbing case.

Figure 6 encases the heading angles compared between the proposed heading control and the former method. It shows that an uncontrolled heading will accumulate over time, so the robot strays away from the intended course.

Comparatively, the controlled run can achieve the set direction of 0° in the long run. Moreover, the robot can maintain its objective at an absolute error of 2.2 degrees.
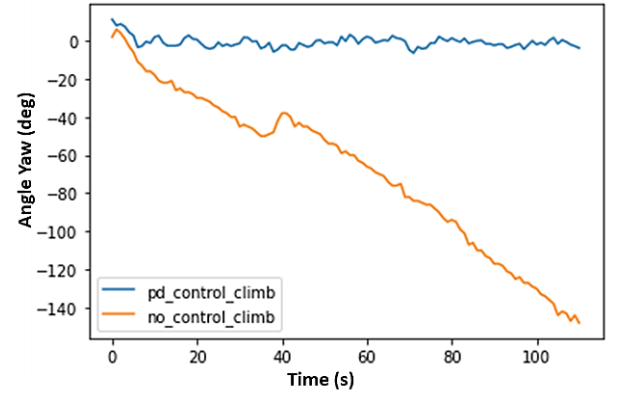

Figure 6. Comparison of heading angle between implementation of heading control and uncontrolled run

The uncontrolled version, however, has a deviance rate of 1.3 deg/s compounding. The deviation from the designated heading accumulates with time. This condition became less of a concern in the former research that dealt with only 20 cm of inclined track and completed within 4 seconds for the inclination. When the size is increased five-fold, it is more concerning since it increases the time needed to at least five-fold. Thus, it will reach almost 26 degrees of deviation, which is not negligible. Therefore, the authors opted out of the execution of stair climbing without the proposed algorithms.

B. *Validation of the proposed method*

The authors then verify the heading control on stair climbing and compare it with the run on a flat surface. The expectation on the subject is that the heading on stair climbing would be less stable than the flat surface. However, the topic that the author is more concerned with is how much it deviates from the designated heading.
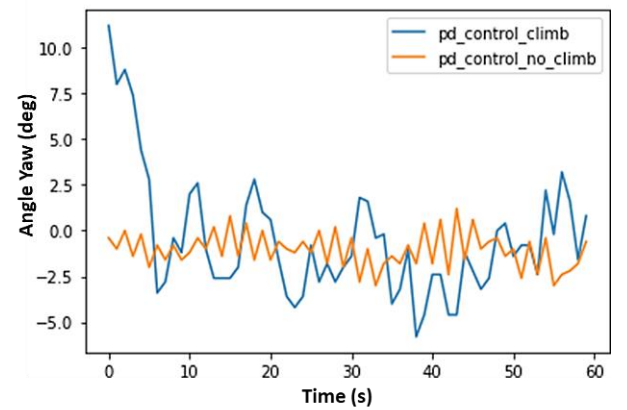

Figure 7. Comparison of heading angle in heading control implementation on a flat surface against stair climbing

Figure 7 exhibits the heading angle error of runs both in stair climbing and flat surface in Figure 7. In both runs, the direction setting for the heading is 0 degrees. The run of climbing stairs is more unsteady than the run on a flat surface. The absolute heading angle error of the stair

climbing is 4.4 degrees. It has an error margin about twice that of the flat surface. However, it is finer than the possibility of a 26º deviation. Logically, the stair climbing run is unsteady even when deploying the heading control since there is no feedback to observe the surface the robot is on.
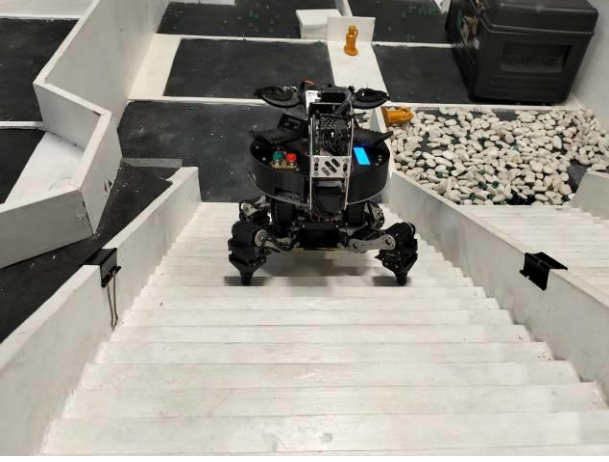
Figure 8. Quadruped climbing the stairs

It is suitable to be implemented on the elongated track of the competition since it is stable in the long run. A spike of 10 degrees occurs at the initial point of the stair climbing. The phenomenon occurs as a by-product of the transition from a flat surface into the stairs, having a high inclination at almost 30 degrees.

C. Robot Mission Performance

The author noticed that the mission in the competition falls into three crucial points: traversing an uneven cracked terrain with rock, marbles, and broken floor pieces, fighting over the dummies to rescue, and stair climbing to the top platform. The stair climbing part required the robot to bring a dummy victim resembling a rescue mission to obtain a perfect score. However, the dummy victim can be taken hold by the opposing team. Therefore, the authors also considered the strategy for ditching the rescue target. Thus, from the originally planned five runs, three carrying the dummy victim while climbing and two without. Figure 8 shows the robot climbing stairs without holding the said rescue target.

The author evaluated the robot mission performance on two key factors: performance speed and heading angle conformity. The time needed to climb the stairs is the base for the speed indicator. The recording starts when a leg touches any part of the stair and ends when the robot reaches the upper part of the competition platform. The stairs length used in the competition is 101 cm. Then, we can obtain the climbing speed by dividing that amount by the climb time. The IMU gathers the data during the mission and monitors the heading angle. The intended heading is 0 degrees. We averaged the absolute error for a single run to obtain the performance of the heading angle. Denote the indicator of heading angle as $\overline{e_\psi}$.

The data in Table 1 shows the results of the planned evaluations. The climb time on the executed runs can reach the shortest time of around 20 seconds and the longest time of 38 seconds. Therefore, it translates into the fastest speed of 5.05 cm/s and the slowest of 2.72 cm/s. It also can be observed that the run with holding a dummy takes more time compared to the run without it. Ditching the target could be a viable strategy to implement as it cuts the climbing time by an average of 10 seconds.

Table 1. Performance of Robot Rescue Mission

	Climb Time (s)	$\overline{e_\psi}$ (deg)	Climb Speed (cm/s)	Hold Target
Data 1	37.84	4.57	2.72	yes
Data 2	30.91	6.26	3.33	yes
Data 3	30.97	4.72	3.32	yes
Data 4	24.00	3.33	4.29	no
Data 5	20.39	2.71	5.05	no

The author observed a significant difference in the average heading angle error between the run while holding a dummy and without. The former had an average error of 5.1 degrees, while the latter had an average of 3.0. The overall error can be expected at a 4.4-degree margin of error on average, while the worst run is 6.26 degrees of error. This fact further supports the strategy of ditching the dummy as a viable option.

There is only a weak correlation between climb time and the heading error averages. Partially, we observed the fact that the decision to hold a dummy puts a burden on the climbing process. The target ironically contributed to the shift of robot inertia and center of gravity. Therefore, the heading became less stable, making the robot slower in finishing the mission.

The author also observed that the robot often slips during the climbing process. In Figure 8, the picture shows that the robot leg tip merely fits the stair steps. When the robot's heading is aligned perfectly with the stairs, its legs are positioned on the steps perfectly. However, when the heading strays and needs to be realigned on the stair, the tip sometimes misses, and the robot slips slightly. However, the balancing algorithm stops the robot from flipping and continues climbing until it reaches the top.

IV. CONCLUSION

The robot presented in this paper has successfully met the author's requirements for the 2023 KRSRI competition. The robot completed the ladder obstacle while maintaining a straight-facing direction with an average margin of error of 4.4 degrees. Furthermore, the robot's speed while carrying a dummy can reach a speed of up to 3.3 cm/s and a faster speed of up to 5.5 cm/s. The succeeding development will be to re-research robot balance control so that the robot can traverse uneven terrain. Additional sensors, especially in the leg, can be implemented in further research to give more feedback to observe the robot's state. The addition of sensors would increase the processing time, making the system slower

and unfavorable for the competition. However, the future application of feedback sensors is a consideration.

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