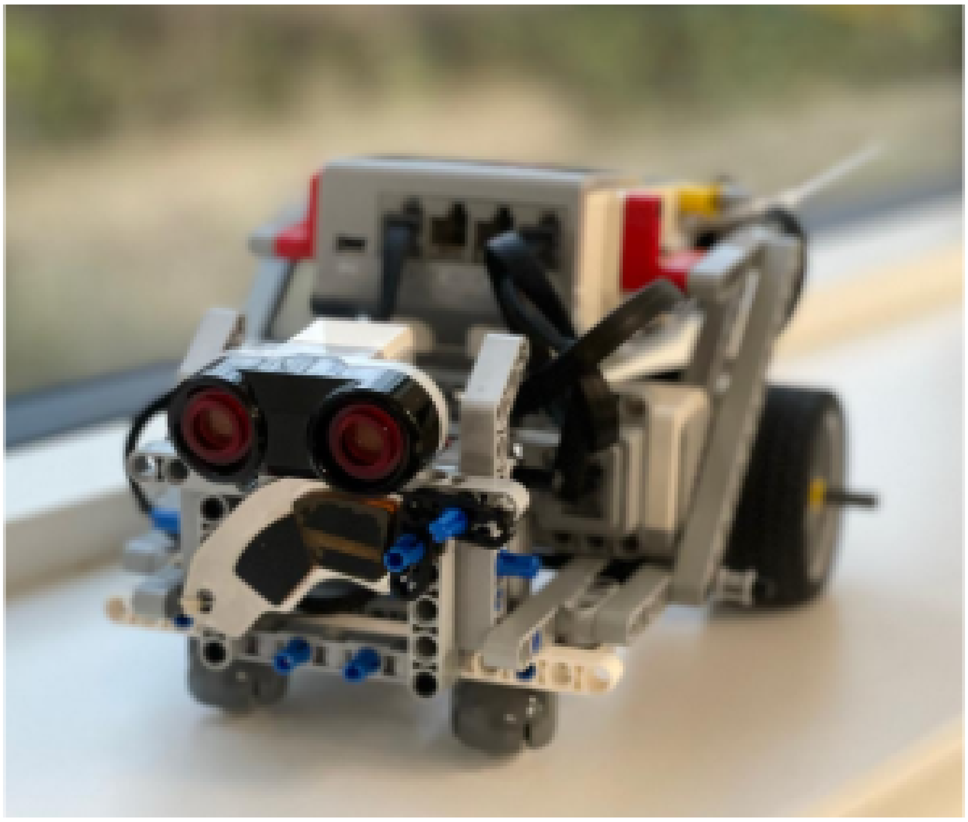
University of Southern Denmark

Education and course:
Advanced Robotics Technology & Drones and Autonomous Systems
Embodied Artificial Intelligence



Submitted by group number 4:
Mounir Abbary – moabb25@student.sdu.dk
Jakub Adam Banaszek – jbana25@student.sdu.dk
Amirhossein Taleshinosrati – amtal25@student.sdu.dk

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1 Project Objective

The goal of the project was to autonomously complete a small “search and rescue” mission using a behaviour-based control architecture. As part of the work, a LEGO EV3 robot was designed and programmed to perform the required tasks. The robot relied on a set of simple behaviors that interacted through a priority-based system, allowing the final control strategy to emerge from the sensor inputs rather than from a predefined sequence of steps. The mission required the robot to follow a black line, detect a can placed within a circular area with a radius of 10 cm, pick it up using a magnet or gripper. After securing the can, the robot continued along the line back to the starting point, completing the entire task autonomously through its behaviors.

2 Construction Stages

2.1 Version 1.0 – Lightweight basic version

The initial design was a lightweight rear-wheel–driven chassis with two independently actuated motors and a single passive front wheel. Two color sensors were put near together and a little bit in front of the wheel axis so they could see the black line. This setup allowed for consistent and responsive line following and was a good starting point for the project. The short wheelbase and low overall mass made it easy to make quick corrections with little effort, and the symmetrical arrangement made sure that the steering was neutral. Putting the sensor close to the steering axis made a clear differential signal, which made it possible to track the line well with moderate PID increases and little oscillation. During early tests, this version was also able to climb the ramp reliably under nominal conditions. Despite its good dynamic behavior, this configuration lacked any mechanism for object collection, making it unsuitable for completing the full search & rescue task. To add a pickup solution while keeping the good control features of this baseline design, more mechanical development was needed.

2.2 Version 2.0 – Servo Gripper and Front Redesign

In the second version, a servo-driven gripper was added so that objects could be picked up. This adjustment changed how the robot’s weight was spread out a lot. It increased the center of gravity forward, which made it tougher to roll, especially on sloped ground. This made it hard for the robot to climb the ramp and follow the line, even after the controller was reset. A metal staple was put in the black line on the ramp to solve a problem on the course. To rectify this, the one front wheel was taken off and two metal ball casters were put in its stead. This change made it easier for the robot to spin and explore since it reduced friction while it was spinning and kept it from becoming stuck on the track. Even with these improvements, the front-heavy layout still affected how well the car worked as a whole. Small changes to the yaw generated significant changes in the lateral sensor, which made tracking less stable and made it take longer to get back on track while going around tight curves. This setup was only transitory because the other concerns were more about structure than algorithms. It was dropped when a lighter magnetic pickup became available.

2.3 Version 3 – Magnetic Gripper (Final Version)

By replacing the servo gripper with a neodymium magnet, the front part became much lighter and it was easier to pick up objects. The nominal drive speed was safely increased from approximately 45 to 70 motor units without destabilizing line following, reducing overall mission time. The ultrasonic sensor was mounted directly above the magnet on the front axis, ensuring consistent target detection aligned with the pickup mechanism. Color sensors were repositioned closer to the surface (approximately 2 cm), increasing contrast and reducing sensitivity to ambient light. Removing the heavy gripper shifted the center of gravity backward, restoring agility in tight turns and stability on ramps. The lighter front end allowed slightly higher proportional gains without overshooting, while integral action remained minimal and derivative action was used primarily to damp fast corrections. A known edge case occurs on sharp 90° turns, where both color sensors may temporarily read white. In such cases, the "last seen black" heuristic may become ambiguous, occasionally resulting in an incorrect turn decision.

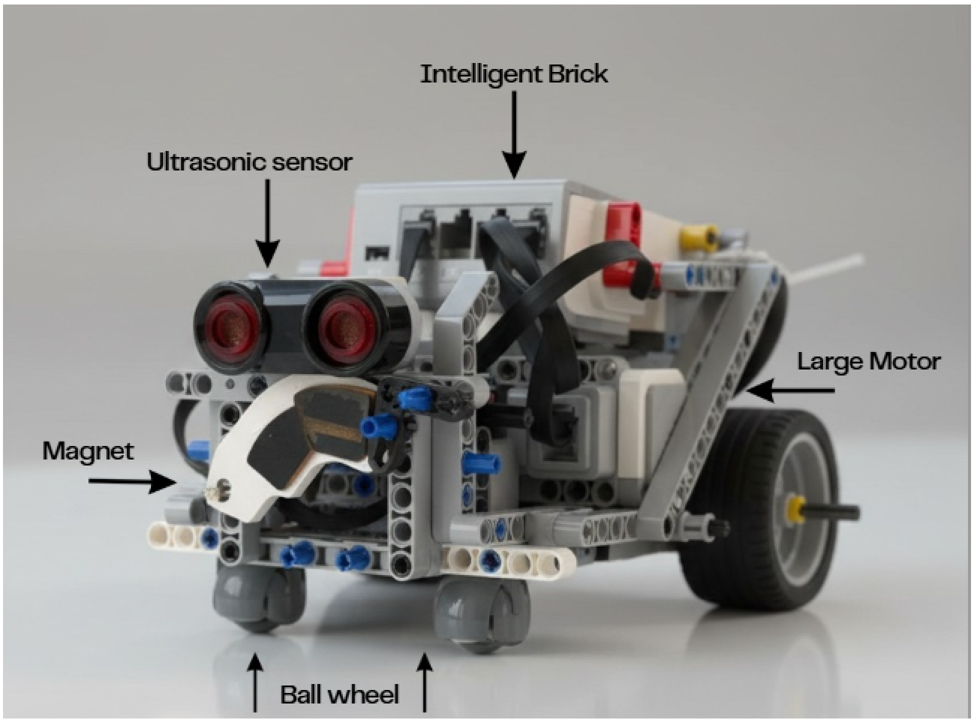


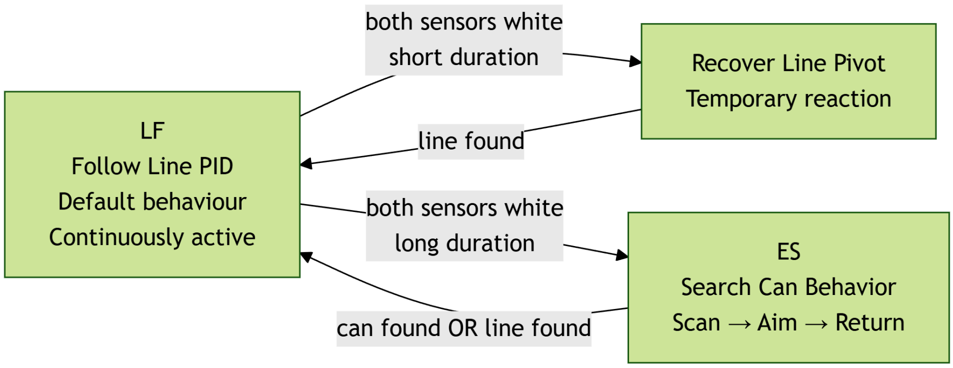
Figure 1: Mechanical design of the robot.

3 Behaviour Architecture

The robot does not execute a fixed script. The system follows a behaviour-based design philosophy. Line following is continuously active as the default behaviour, while recovery and search actions are triggered conditionally based on sensory input, and line following resumes automatically once the line is re-acquired.

3.1 Line Following (LF)

The robot uses a PID corrector for the difference in light reflection on the left and right sides. The system includes explicit logic to distinguish between temporary gaps in the line and the actual end of the line. A gap is detected when both color sensors report high reflectance values (white surface) while maintaining a small difference between them. Short gaps are handled by recovery behavior: the robot performs a pivot motion in the direction suggested by the last known error, increasing the likelihood of reacquiring the line nearby. Counters track how long white readings occur consecutively. If this situation lasts longer than a given duration, the gap is considered the end of the line.



3.2 End of Line Search (ES)

After a short, continuous white reading from both color sensors, the controller temporarily invokes the ES routine when LF detects a persistent white gap. The robot quickly spins toward the side where it last saw black. It uses the last known edge as a guide and does a big but limited rotation to try to find the line again. If the line isn't found within this angle range, the ES behavior moves on to target exploration. The robot initially gets back to its original position, then moves forward in little stages, and finally does an ultrasonic scan from left to right. Distance readings in the range of approximately 40–90 units are interpreted as a valid target. Values below approximately 40 units are explicitly ignored, as they typically correspond to nearby walls or structural elements of the environment rather than the target can. This filtering prevents false positives caused by very close obstacles, which are easier to encounter than the can itself. Upon detecting a valid target within the accepted range, the robot drives straight ahead and the magnetic pickup captures the can. Very large distance readings (around 180 units) are treated as "not yet visible," and the scan is completed without triggering a pickup. If no valid target is detected, the system either continues searching or returns to line following. During the scanning motion, it is possible for a side color sensor to encounter the black track; in this case, line following resumes automatically, which is acceptable from an operational perspective, as either the target has been located quickly or the robot has safely rejoined the guiding path

3.3 Guided Return (GL)

After a successful pickup, the robot returns to the original turning point, restores its orientation, and resumes line following. During this phase, search behaviours are disabled to prevent re-triggering during re-acquisition.

4 Competition Results

The robot achieved first place in the competition. During six official attempts, three runs were completed, with completion times improving across runs (2:21 → 1:58 → 1:48, winning run). The three unsuccessful attempts corresponded to a known extreme case at a sharp 90° turn, in which both color sensors briefly read white and the end-of-line turn selected the wrong direction.

5 Performance Metrics

To evaluate the robot's performance, four quantitative metrics were defined, focusing on both reliability and failure characterization:

- **Section success rate**: fraction of runs in which each mission section was completed without leaving the line or tipping.
- **Search and grab success rate**: fraction of search attempts that resulted in a successful pickup.
- **Return success rate**: fraction of successful pickups followed by a correct guided-line (GL) return.
- **Failure mode count**: number of failures classified as mid-corner failures, dashed-line failures, last-turn failures, and missed cans.

Table 1: Section-wise performance results over 30 trials per stage.

Section	Trials	Successes	Failures	Mean Time [s]	Success Rate
First floor LF	30	26	4	16.00	87%
Ramp	30	24	6	19.79	80%
Second floor LF	30	30	0	17.47	100%
Search & grab	30	27	3	13.67	90%
Return	30	27	3	44.56	90%

5.1 Experimental Protocol

On the official competition map, the mission was divided into five stages: first floor, ramp, second floor, search and grab, and return. Each stage was executed independently 30 times under laboratory conditions. Completion times were recorded in seconds; if a run did not reach the end of a given stage, it was marked as a failure and recorded accordingly. This experimental procedure provided both timing information and an effectiveness indicator for each mission stage.

The resulting dataset consists of 30 trials. The average total mission completion time was approximately 111 s, with a minimum observed time of 108 s and a maximum of 120 s. The relatively narrow interquartile range indicates good repeatability after PID tuning and color threshold calibration.

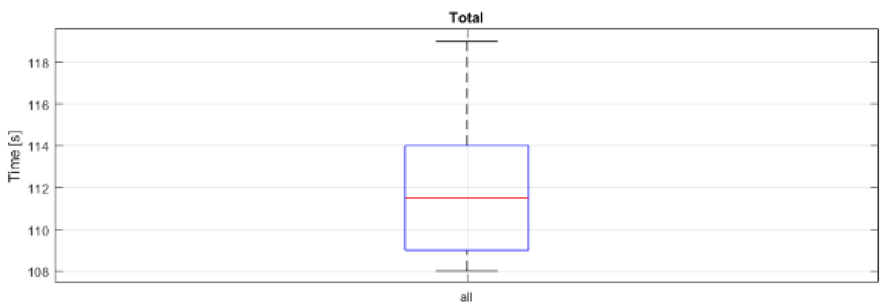


Figure 2: Distribution of total mission completion times over 30 trials.

The highest bar is Return (45 s) – the longest stage. Ramp (19.8 s), Upper (17.5 s), and Lower (16 s) are similar; Search & grab (13.7 s) is the shortest thanks to the magnet (no servo delays). The summary explains where the total time of 111 s comes from and where we have the greatest reserve.

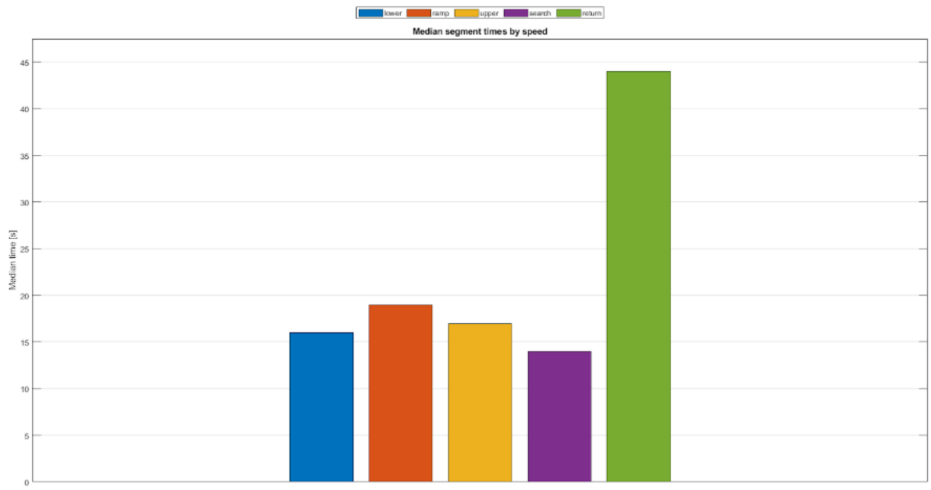


Figure 3: Mean execution time per mission stage, averaged over 30 trials.

It can be observed that, when the mission is divided into individual segments, the largest portion of time is spent on the ramp traversal. This behavior is mainly due to the constraints imposed by line following on an inclined surface. A minimum forward speed is required to climb the ramp; however, at higher speeds the controller performs faster and more frequent left–right corrections. These rapid corrections reduce wheel–ground adhesion and effective forward velocity, resulting in longer traversal times rather than faster ones. For this analysis, the return phase is not considered, since it includes the ramp in descent while performing line following on both the first and second floors. As a result, the return segment is dominated by different dynamics and does not reflect the same control and traction limitations present during uphill ramp traversal. Further performance improvements would therefore require identifying an optimal trade-off between mechanical design (e.g., wheel material and traction) and control parameters, particularly forward speed and PID tuning, in order to maximize stability and efficiency on inclined sections.

5.2 Comparison of Design Variants and Tuning Stages

Although the quantitative tables correspond only to the final magnet-based configuration, qualitative performance trends can be clearly extracted.

5.2.1 Servo Gripper vs. Magnetic Pickup

The servo-based gripper suffered from frequent pickup failures due to strict alignment requirements. Additionally, the robot exhibited backward tipping on the ramp. After replacing the gripper with a magnetic pickup system, the capture success rate improved to approximately 90%, and ramp tipping was eliminated. This modification significantly enhanced both robustness and mechanical stability.

5.2.2 Front Wheel vs. Metal Ball Casters

The original front wheel introduced excessive friction, slower turning, and reduced scanning efficiency during exploration. Replacing it with metal ball casters enabled faster and more precise rotation, which directly improved the performance of the ES (exploration/search) and GL (guided line) behaviours.

5.2.3 PID Tuning and Speed Optimization

At higher speed levels, the same PID gains that were stable on flat terrain produced overly aggressive corrections on the ramp. The combination of slope, curvature, and reduced wheel–ground adhesion amplified lateral oscillations, frequently leading to mid-corner failures. In this regime, rapid left–right corrections reduced effective traction and destabilized the robot rather than improving tracking accuracy. Stability on the ramp was achieved by jointly adjusting forward speed and controller aggressiveness. Limiting the ramp speed reduced the effective control gain, allowing proportional action to correct deviations without inducing oscillations.

5.3 Embodiment Analysis

Control algorithms alone cannot fully explain the robot's performance. Decisions in mechanical design were very important for making control easier and making the system more stable. The use of a magnetic pickup made it unnecessary to control perfect alignment, and the use of metal ball casters made turning easier by reducing friction. These embodiment decisions, along with better PID gains and speed limitations, turned an unstable early prototype into a dependable autonomous system. The final configuration illustrates how effective co-design of mechanics and control significantly improves autonomous robot performance.

Metric	**Value (mean ± std)**	**Notes**
Line-following speed	70 ± 3 motor units	Stable tracking
Line reacquisition distance	2.0 ± 0.0 cm	After short interruptions
Target detection range	70 ± 10 units	Ultrasonic window
Full mission success rate	93%	Failures on sharp 90° turns
Mean mission completion time	48.5 ± 4.3 s	Start to final return

Table 2: Performance summary for the final magnet-based configuration.

6 Discussion

The results demonstrate that the proposed behavior-based architecture prioritizes reliability and robustness over raw execution speed. This design choice fits well with the needs of an autonomous search-and-rescue task, which has to work under strict physical and sensory limits.

The chosen performance measures emphasize successful job completion and failure characterization instead of optimal timing, facilitating a definitive evaluation of system stability during various mission phases.

The ramp was the hardest part of the environment in all of the experiments. To get over gravity and keep going up, you need to move at least a certain speed on a ramp. This is different from flat ground. But if you go faster than this point, the line-following controller becomes less stable.

As you move faster, the changes to the side get bigger. This means that the wheels don't stick to the ground as much and the car sways more when it turns. You need to know how fast to go up a ramp and how careful to be to preserve your grip and balance in order to do so securely.

The comparison of design options reveals how crucial embodiment is for making control easier. The robot's front was less likely to go out of alignment and shatter when the servo-driven gripper was replaced with a magnetic pickup. It was clear right immediately that the truck and the ramp were both more stable and dependable.

Using metal ball casters also made it easier to rotate things since they reduced friction, which made exploration and guided-line behaviors operate better. It's important to note that these gains were made without adding more sensors or making the controls more complicated, but they did make the system much more resilient overall.

Even while the system works well most of the time, it has a clear problem when both color sensors lose the line at the same time, like when the car makes a quick 90° bend. It's not always easy to understand the "last seen black" heuristic, which can make it challenging to estimate which way to turn.

This failure mode doesn't happen very often at the chosen operating speed, but it shows the trade-off between minimum sensing and perceived redundancy. We would need either more sensors or better logic to get back on track after a line loss to fix this problem.

The results substantiate the fundamental premise of embodied artificial intelligence: resilient autonomous behavior arises from the intricate interrelation of mechanical design, sensor positioning, and straightforward control principles.

The system gets consistent performance not by using complicated planning or exact location, but by making the right co-design decisions. This shows that in real-world activities with limited resources, simplicity and physical awareness can be better than algorithmic complexity.

7 Conclusion

The project was a complete success, meeting all the objectives of the proposed search & rescue mission. The robot's mechanical design proved effective in every key aspect. The center of gravity was positioned such that the robot could climb the ramp without slipping, while the structure remained robust enough to withstand impacts during descent.

In particular, the front assembly was designed so that the collected can absorbed part of the collision energy when hitting the lower wall, preserving the integrity of the supporting structure and Technic connections.

The introduction of a magnetic pickup eliminated several limitations associated with servo-driven grippers, such as actuation delays and incomplete closure. This resulted in repeatable and reliable object acquisition, as well as stable and predictable "Search & Grab" times across trials.

On the control side, the behavior-based architecture with priority arbitration proved effective in practice. Line following operated as the default behavior, transitions to end-of-line detection and search were smooth, and the guided return after pickup was consistently reliable.

The main limitation identified in the current implementation concerns very sharp 90° turns, where the ambiguity of the "last seen black" heuristic can occasionally lead to incorrect turn decisions. This issue could be addressed in future iterations by increasing perceptual redundancy, for example through the addition of a third color sensor, or by refining the line-loss recovery logic.

Furthermore, several mission stages still exhibit time margins that could be reduced through additional optimization, particularly in line reacquisition behaviors.

In summary, the robot reliably follows the line, detects and picks up the can in the designated zone, and successfully returns to the starting point. The mechanical design is robust, the control strategy is stable, and the experimental results, including the winning competition run of 1:48, confirm that the system achieves a strong balance between simplicity, reliability, and effectiveness.

These qualities are precisely what matter most in practical autonomous search- and-rescue tasks.