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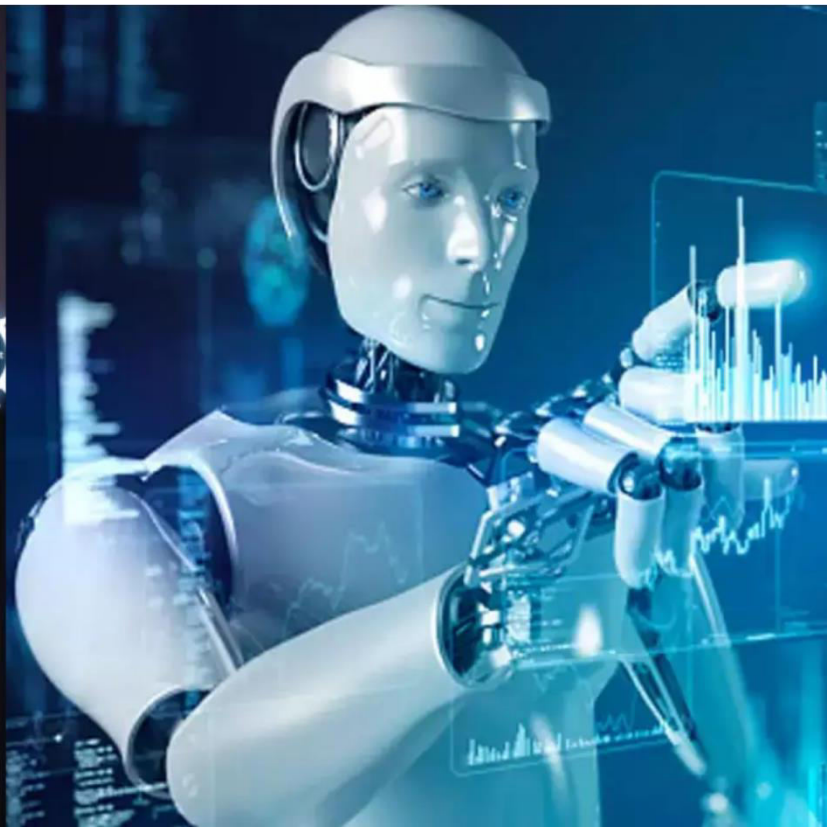

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Design and Development of an Autonomous Robot for Toxic Gas Monitoring and Oxygen Level Detection in Underground Mines

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ABSTRACT: A tracked robot surveying a mine tunnel can move several metres while a gas sensor responds to a change in concentration. Assigning the resulting reading to a single point on a map can obscure the location of that change. This Phase 1 thesis examines the relationship between travel speed and sensor response in Navigator, a proposed robot for monitoring toxic gases, methane and oxygen. The design pairs each observation with its acquisition time, estimated position and calibration state. We use the specified oxygen sensor response to calculate the travel distance during a concentration step and examine the effect of three survey speeds. At 0.20 m/s, the robot would travel 3.0 m during the sensor's typical 15 s response to 90% of the step. Reducing the speed to 0.05 m/s reduces this distance to 0.75 m. These calculations motivate a paired comparison of continuous travel and stationary sampling at marked checkpoints. The proposed test measures location error and survey duration separately. Sensor dynamics in the assembled inlet, position accuracy and underground performance await experimental evaluation.

KEYWORDS: Mobile gas sensing, underground mines, sensor response time, gas distribution mapping, mobile robotics.

I. INTRODUCTION

A post-blast survey asks where hazardous conditions persist along a route and when each location was last sampled. A robot can carry an instrument ahead of an operator, but interpreting the resulting map requires two positions: the position where the atmosphere changed and the position where the instrument registered that change. Even perfect localization would leave a discrepancy if the robot moved while the sensor responded.

Navigator is in Phase 1 of development. Prototype design and procurement of selected components are underway. The system described here is the proposed configuration for a laboratory study of gas sampling in a GPS-denied tunnel. The design question is whether moving observations can resolve a change within a specified distance along the route, or whether the robot should stop at selected checkpoints. We examine that question for a six-channel instrument by linking the time scale of each measurement to vehicle speed. The scope is a laboratory prototype at a fixed inlet height.

II. RELATED WORK

Kim and Choi combined autonomous ground patrols with environmental sensing in an underground mine [1]. Nordström et al. demonstrated autonomous gas inspection after blasting using an aerial platform [2]. These studies establish the feasibility of robotic access and spatially referenced measurements in their respective field settings. Their results do not establish the accuracy of a different sensor assembly on a tracked vehicle.

Lilienthal et al. modelled both the mean and variance of gas concentration from localized observations [3]. The quality of such observations depends in part on sensor dynamics. Monroy et al. modelled distinct rise and recovery behaviour in metal-oxide sensors [4]. Navigator retains the raw observation, its time and its estimated position so that the effect of motion can be assessed before concentrations are estimated between sample locations.

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III. PLATFORM AND MEASUREMENT METHOD

The proposed robot carries a horizontal laser scanner and an atmospheric sampling inlet on a steel tracked chassis. A Raspberry Pi 4 Model B (4 GB) running ROS 2 would maintain a two-dimensional map and log observations. An STM32 NUCLEO-F446RE would control the drive and acquire conditioned analogue signals [5, 6]. The RPLIDAR A2M12 has a specified minimum range of 0.2 m and ranges of 12 m for white targets and 10 m for black targets under the manufacturer's test conditions [7]. Scan matching would estimate motion relative to the map. An ICM-42688-P inertial unit and track encoders would provide motion estimates between scans [8]. Track slip and repeated tunnel geometry are potential sources of pose error.

Each record would contain the channel, value, unit, acquisition time, sampling mode and calibration status. A common time base would allow the logger to associate a reading with the pose of the inlet, accounting for its offset from the robot centre. A missing pose leaves the observation available in the time log. An out-of-range reading retains its flag. The map would display observation times and sampled locations so an operator could distinguish a recent measurement from an earlier visit.

Table I gives the manufacturer's concentration ranges for the selected channels. Each channel requires its own acquisition circuit and calibration. The methane channel reaches its upper limit at 1.0% by volume. A survey requiring higher concentrations would need a different instrument. The inlet must admit ambient air to the sensing elements while protecting the electronics. The enclosure's IP67 rating describes ingress protection. Qualification of the assembled robot for explosive atmospheres remains outside the present design analysis.

TABLE I. PROPOSED LABORATORY SENSOR CHANNELS

Gas and sensor	Nominal range	Acquisition constraint
CO · MQ-7B [9]	10–500 ppm	60 s hot and 90 s cool heater phases. Record the phase with each reading.
H_2S · MQ136 [10]	1–200 ppm	Heated resistive sensor. Characterize interfering vapours during calibration.
NO_2 · MiCS-2714 [11]	0.05–10 ppm	Typical NO_2 range. Provide heater control and a resistance readout.
SO_2 · SO_2-B4 [12]	0–100 ppm	Four-electrode cell with a low-noise current readout. Specified $t_{90} < 60$ s for a 0–2 ppm step.
CH_4 · MQ-4 [13]	300–10,000 ppm	Heated resistive sensor. Retain an out-of-range flag above the calibrated interval.
O_2 · KE-25LF [14]	0–30% by volume	Galvanic cell with millivolt output. Typical $t_{90} \approx 15$ s at the specified air exchange.

The laboratory design uses the Pi's wireless LAN for telemetry and remote intervention. The controller would stop the drive on loss of a fresh remote command and continue logging locally. A regulated 5 V supply rated for at least 3 A serves the Pi [5]. The motor and instrument supplies require separate current allowances. Gross mass, sprocket radius, target grade and stall current remain inputs to motor, driver and battery-protection sizing.

IV. ANALYTICAL RESULTS AND DESIGN TRADE-OFFS

Consider an inlet travelling at constant speed v across a sharp, stationary concentration boundary on a straight route. Let t_{90} denote the time for the output to reach 90% of the difference between its initial and final indications. The distance travelled in that interval is $d_{90} = v\, t_{90}$. This kinematic relation requires no assumption about the shape of the response curve. It provides a distance scale for a step change. Actual boundary-location error also depends on the detection rule, inlet transport, airflow and pose estimation.

For the KE-25LF, using the typical t_{90} of 15 s [14] gives distances of 0.75, 1.50 and 3.00 m at speeds of 0.05, 0.10 and 0.20 m/s. To keep travel during that interval within an illustrative 1 m allowance, the limiting speed is 1/15 m/s, approximately 0.067 m/s. Choosing a finer map grid leaves the physical response distance unchanged.

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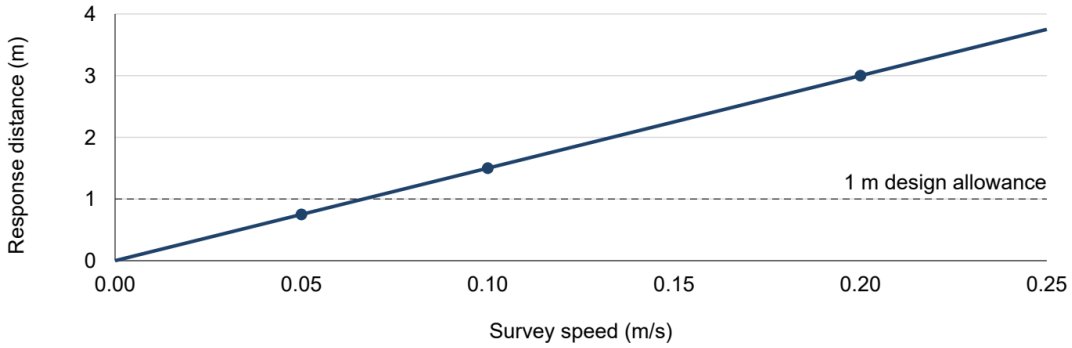

Fig.1. Calculated distance travelled during a 15 s oxygen-sensor response. Dots mark the three illustrative survey speeds.

The CO channel imposes a different constraint. If one comparable reading is retained per complete MQ-7B heater cycle, consecutive observations are 150 s apart [9]. At 0.20 m/s their positions would be 30 m apart. This is sample spacing under the stated acquisition policy. Heater-cycle duration and step-response time describe different processes. A checkpoint mission would need to schedule arrival and dwell against both.

The original component allowance (Table II) was INR 56,850, including INR 7,300 for gas sensing. It predates selection of the SO_2 cell, its readout and the revised oxygen channel. The 12 V, 20 Ah battery specification corresponds to 240 Wh nominal energy. Estimating mission duration requires usable energy and the mean load over both motion and dwell. Longer stops may improve settling while reducing the route length achievable per charge.

TABLE II. ORIGINAL COMPONENT ALLOWANCES USED IN THE FEASIBILITY STUDY (INR)

Subsystem	**Original scope**	Allowance (INR)
Structure	Chassis, enclosure, tracks and suspension	14,000
Power	Battery pack, battery management and wiring	9,300
Control	Processor, controller and storage	7,600
Navigation and drive	Laser scanner, inertial unit and motor drivers	17,000
Gas sensing	Allowance for the original six-channel array	7,300
Communication and alerts	Radio, indicators and buzzer	1,650
Total	Original planning allowance	56,850

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V. PROPOSED EVALUATION AND LIMITATIONS

The primary endpoint is the along-route distance between a known concentration transition and the position assigned to that transition by the mapping system. The secondary endpoint is total survey time. A controlled comparison would use the same course, sensor configuration and checkpoint locations for both moving and stationary sampling. Clock synchronization, inlet height and the inlet's offset from the robot centre would be recorded before each run.

A first test would inject a time-stamped synthetic step as the robot crosses a surveyed mark. The run would verify the sign and magnitude of time-to-pose errors with the physical gas sensor bypassed. Separately, a supervised laboratory instrument comparison would measure each assembled channel's rise and recovery times, bias and repeatability using a calibrated reference. The stored reference trace and the measured response could then be replayed against both sets of route logs to isolate the effect of sampling policy. This replay addresses a fixed input. A physical trial with an independently measured spatial profile would be needed to evaluate a changing atmosphere.

TABLE III. COMPARISON OF SAMPLING MODES ON A MARKED COURSE

Outcome	Comparison method	Reported quantity
Position	Compare estimated inlet poses with independently surveyed checkpoints.	Along-track and cross-track errors (m)
Transition location	Use the same crossing rule for both modes, referenced to the independently recorded step.	Signed and absolute displacement (m)
Coverage and time	Match the route and travel speed. Record dwell, missing samples and incomplete runs.	Survey time (s), valid observations per metre
Energy and link	Log pack voltage, current and packet sequence numbers throughout each run.	Energy per survey (Wh), longest telemetry gap (s)

For a rising step, normalize the reference and sensor traces to their pre-step and final levels. Define a crossing at the first observation reaching 90% of the step. For checkpoint data, also report the interval between the last checkpoint below the criterion and the first above it. Its width gives the spatial resolution of that sampling scheme. A run that never reaches the criterion is recorded as a missed transition.

Pair runs by route and direction, alternate mode order and repeat in both directions. Report the number attempted and completed, each paired difference, and the median and range. A sign reversal in the displacement, expressed on a fixed route axis, would be consistent with a directional lag. A reproducible error at the same map location would warrant checking the pose estimate and reference coordinates.

VI. CONCLUSION

For the proposed oxygen channel, a typical 15 s response spans 3.0 m at 0.20 m/s. If a survey requires observations within a metre of a stationary transition, slower travel or a dwell at a known location deserves testing. The practical choice depends on the installed sensor response, localization error and time available for the route. The Phase 1 analysis identifies survey speed and checkpoint dwell time as design variables. Once the prototype is assembled, paired runs on a marked course can establish the trade-off between location error and survey time.

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