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Robotic system for indoor illuminance map generation

Rémy Guyonneau^{a,*}, Franck Mercier^a and Vincent Boucher^{a,b}

^aUniv Angers LARIS SFR MATHSTIC F-49000 Angers France

^bLight and Lighting Team, Cerema, 23 Av. Amiral Chauvin, Les Ponts-de-Cé, 49130, Pays de la Loire, France

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ABSTRACT

The paper describes Romulux, a mobile robot equipped with 3D LiDAR carrying an illuminance meter and dedicated to measure indoor lighting quantity. The aim is to check compliance with lighting standards in terms of level and uniformity. The general architecture of the robot using the Robot Operating System (ROS) is presented, and technical choices are explained according to the different constraints. The space localization of illuminance data is computed with Synchronous Localization And Mapping (SLAM) algorithms. Then measurements are compared to standards requirements and interpolated into a user-defined grid to generate a dense illuminance map. Two experiments, one in a sport hall and one in an ice rink, are presented and results are exposed. The paper will follow the workflow from designing a robot to a functional system able to generate illuminance maps, compare with standards and save energy in case of over lighting.

1. Introduction

Lighting requirements are determined by the satisfaction of three basic human needs: visual comfort, visual performance and safety. The quantifiable parameters subject to the requirements CEN (2021a) CEN (2021b) are the illuminance (amount of light arriving on a surface), its uniformity, the discomfort glare and the color rendering index. When constructing a building, the type and number of lighting elements are sized according to those lighting standards, depending on use of the site if it concerns a hospital, a warehouse, a home, etc. European standards also exist for the lighting of sports facilities CEN (2018), which ensures good visual conditions for players, athletes, referees, spectators and for color TV broadcasting. The objective is to specify recommendations and requirements to produce good quality lighting for sports facilities ensuring the needs of all users. This is done by optimizing the perception of visual information used during sports events, maintaining the level of visual performance, providing acceptable visual comfort and limiting obtrusive light. Standards provide values for lighting control in terms of illuminance, uniformity, glare control and color properties of light sources. It also provides mesh-grids for measuring these values CEN (2018).

To meet the standards, it is usually appropriate to carry out a control operation by measuring the illuminance. This operation is done by an operator equipped with an illuminance meter, who must perform spot measurements. The steps are

- Referencing the location of the measurement within a normative mesh-grid;

- Moving away from the illuminance meter to perform the measurement;
- Recording the measurement.

The operation must be done many times in order to achieve a relevant mesh of the area of interest Akashi and Boyce (2006). This operation is tedious and time-consuming. In practice, this operation is rarely done. Instead, installers tend to over-light to ensure compliance with standards.


The automation of controls is interesting in many ways because it could provide better suitability with the standards: the control will be actually done, the quality of the measurements will be constant and not subject to the human operations uncertainties. A better compliance with the standard could lead to:

- Improve user comfort since the standards are studied in particular with regard to this criterion;
- Save energy thanks to the readjustment of the installation lighting power. This can be easily done, for instance, with dimmed LED lights.

Evaluating lighting quality is of interest to reduce energy consumption Li (2010) Muzet, Colomb, Toinette, Gandon-Leger and Christory (2019a) Muzet, Greffier, Nicolai, Taron and P.Verny (2019b), to predict building integrated performance Todorovic and Kim (2012), to implement lighting control algorithms Mohammad, Hassan, Abdullah, Rahman, Abdullah, Hussin and Said (2014), Guillemin and Morel (2001), to evaluate visual comfort Nabil and Mardaljevic (2005), Akashi and Boyce (2006) or also to manage road lighting Kumar and T (2022); Greffier, Boucher, Muzet, Buschmann and Völker (2023).

Lighting quality evaluation is then based on illuminance measurements related to spatial locations Carter, Sexton and Miller (1989). For outdoor applications, those locations are generally recorded thanks to a Global Navigation Satellite System (GPS for instance) J. and Oliver (2017). But for indoor applications, this technology is no more available

*Corresponding author

 remy.guyonneau@univ-angers.fr (R. Guyonneau);

franck.mercier@univ-angers.fr (F. Mercier); vincent.boucher@cerema.fr (V. Boucher)

 <http://perso-laris.univ-angers.fr/~r.guyonneau/> (R. Guyonneau)

ORCID(s): 0000-0002-9242-2854 (R. Guyonneau); 0000-0003-1663-1651 (F. Mercier); 0000-0003-2299-4168 (V. Boucher)

and an alternative has to be found. The LiDAR technology has been chosen here for its performance regarding the detection range Warren (2019). To deal with the standards requirements and to acquire quickly and easily data along a specified mesh-grid, an automated illuminance acquisition system has been developed aiming to construct illuminance maps of a room.

A robot has been designed for an indoor environment. The problem of automated lighting measurement is an active research domain. Attempts are made to perform this task, but encounter localization problems Tang, Inoue, Oshio, Tsujimoto, Taniguchi and Kubota (2020) He, Wang, Zhao, Hao, Hu, Tong, Jiang and Shao (2021) Oshio, Tsujimoto, Taniguchi, Obo and Kubota (2022), or demonstrate the ability to perform localized measurements in extremely controlled environments Drábek, Petrík and Holub (2020). The contribution of this paper is twofold:

- On the design of the platform which is very accomplished and robust in face of localization issues;
- On the expertise of the illuminance measurements by going to the end of the process with illuminance maps.

The paper is organized as follows: first the mechanical and technical specifications of the system are described, then some experiments and results are presented, and the final section concludes and draws perspectives for this approach.

2. Requirements, solutions and platform presentation

2.1. Objectives, constraints and environment

The objective for developing a robot is to ease the illuminance mapping of indoor environments. To that purpose the robot must:

- Acquire illuminance measurements;
- Locate those measurements in the environment.

However, indoor environments have characteristics that should be considered for robot design. Admittedly, the ground is flat and presents little disturbances (door threshold, concrete threshold bar, electric cables, etc.), but more insidious difficulties may appear (tables, chairs, structural posts, etc.) and lead to both navigation avoidance, and more complex mapping. These constraints must guide the form factor of the robot and its kinematic model for the maneuverability of the system.

The illuminance measurements are governed by standards. In order to comply with EN 12193 CEN (2018) and EN 12464 CEN (2021a) CEN (2021b) standards, the illuminance is measured by a calibrated illuminance meter. The spectral characteristics of the photo-diode make it conform to the human eye sensitivity and constitute a key point in measuring illuminance (Figure 1). Here, our illuminance meter is made of a commercial luxmeter OPT3001 associated with a diffuser dome and has been calibrated thanks

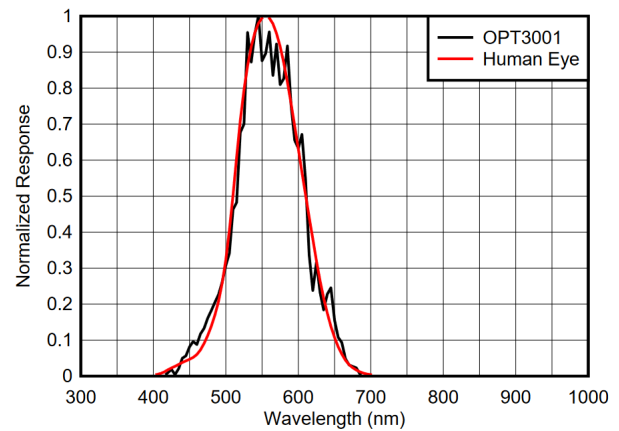


Figure 1: The OPT3001 and Human Eye sensitivity.

to an integrating sphere. This sensor has a measurement range from 0.01 lux to 83 k lux. The illuminance meter is carried by the robot and it has been decided to place it at a maximum height of 25 cm above the floor to keep the results comparable to those made on the floor. The illuminance meter owns two integration times of 100 ms or 800 ms depending on the noise sensibility mode. Regarding to the robot velocity, the shorter integration time has been selected. According to a robot speed around 1 m/s, an illuminance measurement is integrated over 10 cm. Moreover, the sensor must not be in the shadow of any other component. The placement height in addition to shadow avoidance forces the integration of the illuminance sensor at the top of robot.

Another constraint is to leave clearance for the localization sensor (360° LiDAR). Both sensors (LiDAR and illuminance sensor) therefore have the same placement requirement: to be at the top of the robot. The proposed solution is to place the illuminance meter on top of the LiDAR at its centre. It allows an agreement at the cost of a loss of vision in a 20° cone behind the LiDAR sensor. This solution has the advantage to avoid a transformation between illuminance sensor and LiDAR localization. Figure 2 illustrates our implementation of the illuminance sensor above the LiDAR sensor. The location of illuminance measurements will be provided by Synchronous Localization And Mapping (SLAM) algorithms Birk and Pflingsthor (2016); Bautin, Lucidarme, Guyonneau, Simonin, Lagrange, Delanoue and Charpillat (2013).

2.2. Kinematic study

Kinematic with high maneuverability is useful for indoor mobility. The choice has been oriented on a 4 wheels robot, including 2 wheels with stabilizer bar (or anti-roll bar). This prevents ground irregularities and increases the stability of the robot. Moreover, due to the requirement of high maneuverability, differential kinematic appears to be a good solution. Thus, the chosen kinematic is 2 differential wheels with 2 castor wheels on stabilizer bar. This model allows higher mobility than Ackermann steering, up to rotation only Salem (2013).

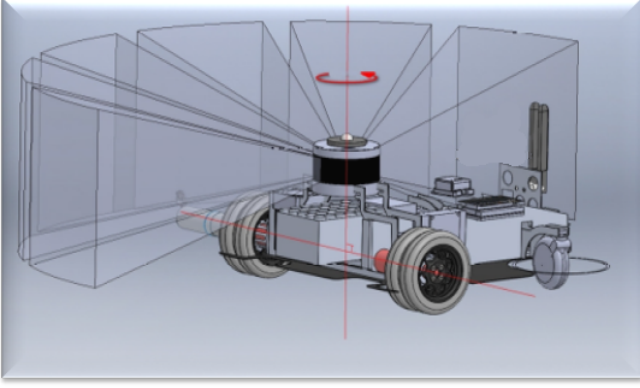


Figure 2: Sensor alignment: the illuminance sensor (little white dome) is above the LiDAR sensor (black tower). Both are aligned over the rotation center of the robot.

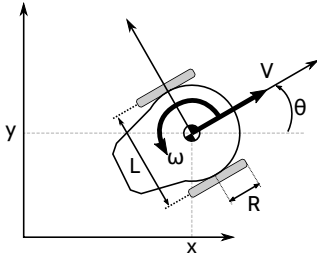


Figure 3: Differential drive kinematics.

To avoid additional transformation between the several frames of the system (sensors and robot's chassis), the LiDAR and illuminance sensors are aligned with the center of rotation (CoR) of the robot.

The sensors placement is illustrated in Figure 2 while Figure 3 shows the different variables related to robot kinematics.

In the world frame, the speed of a differential robot can be represented by:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} V \cos \theta \\ V \sin \theta \\ \omega \end{bmatrix}, \quad (1)$$

with $(x, y)^T$ the position of the robot, θ its orientation, V the linear speed and ω the angular speed. In a context of differential architecture, these two speeds can be expressed as a function of wheel speed of the form:

$$\begin{bmatrix} V \\ \omega \end{bmatrix} = \begin{bmatrix} R/2 & R/2 \\ R/L & -R/L \end{bmatrix} \begin{bmatrix} v_r \\ v_l \end{bmatrix}, \quad (2)$$

with R the radius of the wheels, L the distance between the wheels and v_r and v_l respectively the speed of the right and left wheels in rpm.

Doing so, the Jacobian \mathbf{J} of the system is:

$$\mathbf{J} = \frac{R}{2L} \begin{bmatrix} L & L \\ 2 & -2 \end{bmatrix}. \quad (3)$$

Depending on a linear V and angular ω speed set-point, it is possible to compute the corresponding wheel speed using Equations 2 and 3:

$$\begin{bmatrix} V \\ \omega \end{bmatrix} = \mathbf{J} \begin{bmatrix} v_r \\ v_l \end{bmatrix}, \quad (4)$$

$$\begin{bmatrix} v_r \\ v_l \end{bmatrix} = \mathbf{J}^{-1} \begin{bmatrix} V \\ \omega \end{bmatrix} = \frac{1}{2R} \begin{bmatrix} 2 & L \\ 2 & -L \end{bmatrix} \begin{bmatrix} V \\ \omega \end{bmatrix}. \quad (5)$$

It is the relation of Equation 5 that is implemented in the low level functions of the robot.

2.3. General Architecture

Figure 4 depicts the general architecture of the robot, named Romulux, the robot which measures lux. The CPU unit centralizes sensors acquisition, interface commands and controls the motors while communicating and recording all Robot Operating System (ROS) topics¹.

For general requirement, it is wanted an autonomy of operation of one hour, which defines the size of the batteries. Indirectly the DC/DC converters take into account consumption and capability of upstream and downstream systems. Two 24V brushed DC motors are used to motorize the robot. Those have a 28:1 metal gearbox, provided by Maxon. No coder are embedded as it is assumed that the LiDAR will be used for trajectory following and steering. The couple motor/reducer is able to produce 1Nm torque and a rotation speed above 220rpm, corresponding to a linear full speed above 3m/s. The motors are controlled by Sabertooth card², and communicate through serial communication with the processor, a Nvidia Jetson TX2³. The general architecture of the proposed solution is presented in Figure 4. The LiDAR sensor is a Velodyne Puck⁴ @15Hz scanning at 360° with vertical slices between -15° and +15° and a 100m range with a typical ± 3 cm accuracy. The chassis depicted in Figure 5 has been entirely designed and built to respect the maximum height of 25cm for the illuminance sensor. The maximum speed is therefore set at 3m/s with a working speed of around 1m/s.

Romulux software architecture is based on ROS Quigley, Conley, Gerkey, Faust, Foote, Leibs, Wheeler, Ng et al. (2009). ROS is based on a communication model based on nodes and topics. Nodes are autonomous processes that perform specific tasks, such as controlling a robot's motors or processing data from sensors. These nodes can communicate with each other by publishing or subscribing to topics. Topics are virtual communication channels that allow nodes to share messages asynchronously. A node can publish messages on a specific topic, while other nodes can subscribe to this topic and receive these messages. This flexible and

¹<http://wiki.ros.org/en/ROS/Tutorials/UnderstandingTopics>

²<https://www.dimensionengineering.com/datasheets/>

Sabertooth2x25v2.pdf

³<https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-tx2/>

⁴<https://velodynelidar.com/products/puck/>

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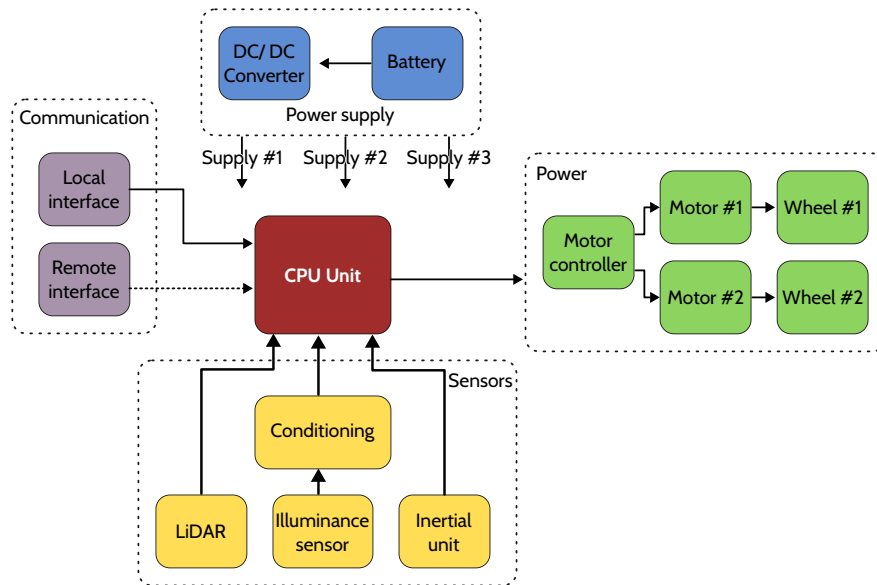


Figure 4: Romulux architecture.

decentralized communication architecture allows different components of a robotic system to operate independently and easily interface with each other. Thanks to the ROS architecture and specifically the twist⁵ data format, it is quite easy to change the remote device. For the presented experiments, a Dualsense Playstation controller has been considered. The connection between the remote controller and the robot is a Bluetooth link. The working range for this remote has been measured up to 30 m, which allows a fine control in visual range of operator without being too close from the robot and thus corrupting the illuminance data. While the robot is being controlled, all the data (LiDAR, illuminance...) are recorded into rosbag files⁶. Those allow to replay the data afterward as if the robot was moving in real time. In this scenario, the illuminance map is built off-line. One of the primary experiment is depicted on the following video⁷ where the SLAM result has been added afterward.

According to the block diagram presented in Figure 4, each wired input/output of the CPU Unit corresponds to a node which interacts with the main node for control or acquisition. A graphical representation is given in Figure 6. Thanks to this architecture, it is quite easy to add or update sensors. The following section presents experiments and results based on that hardware/software architecture.

3. Experiments and results

3.1. Romulux experiment 1

The first scenario took place in a sports hall (30m long x 20m wide), where illuminance constraints are specific to this type of infrastructure. Figure 7 depicts Romulux in the experimental conditions. Different SLAM algorithms (HDL

⁵http://wiki.ros.org/geometry_msgs

⁶<http://wiki.ros.org/rosbag>

⁷<https://youtu.be/0PwFAdcqaLE>



Figure 5: Views of Romulux Robot.

Graph Slam Koide, Miura and Menegatti (2019), LeGO LOAM Shan and Englot (2018) and LOAM Ji and Sanjiv (2017)) have been investigated. What is targeted through the evaluation of several SLAMs is the evaluation of the localization precision. Two approaches are available: comparison of absolute path Burgard, Stachniss, Grisetti, Steder, Kümmerle, Dornhege, Ruhnke, Kleiner and Tardös (2009); Mahrami, Islam and Karimi (2013), or cross comparison of

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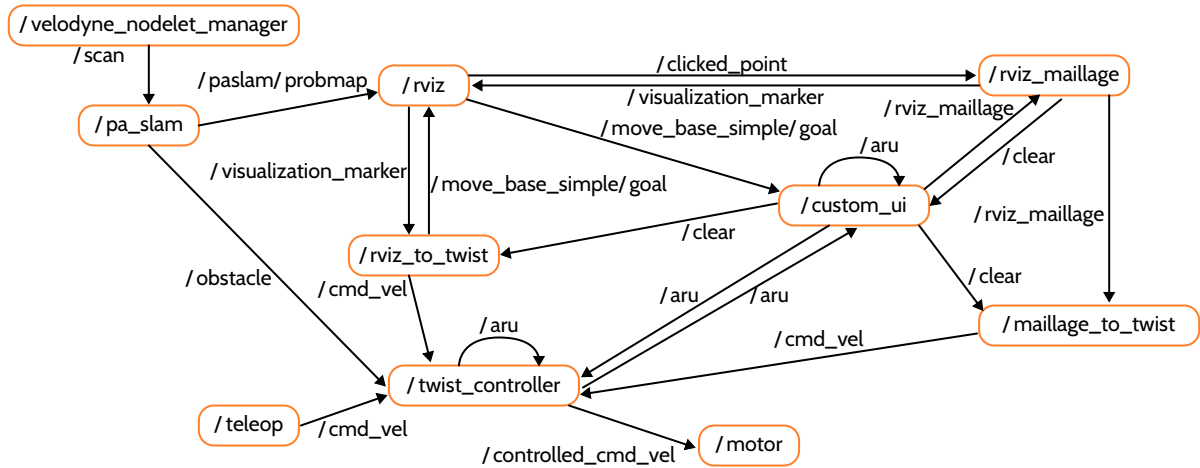
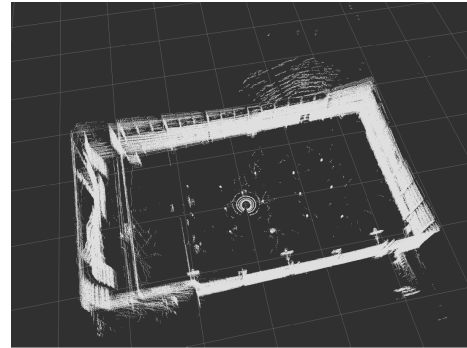


Figure 6: ROS Architecture with nodes and topics



Figure 7: Romulux in the sports hall.

a) Sports hall point-cloud.



b) SLAM paths.

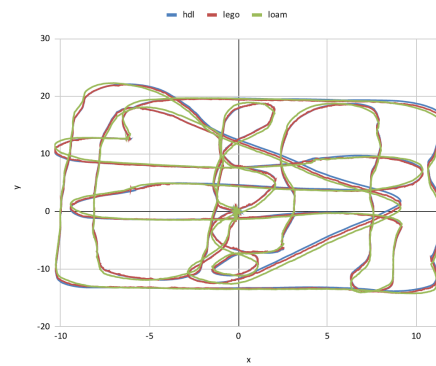


Figure 8: Cross comparison of SLAM path generated.

| | HDL | LeGO |
|------|------|------|
| LeGO | 0.43 | |
| | 0.31 | |
| | 1.53 | |
| loam | 0.59 | 0.71 |
| | 0.33 | 0.17 |
| | 1.53 | 1.11 |

Table 1

Cross comparison between algorithms. In each are the differences between the paths of the algorithms: from top to bottom the mean, the standard deviation and the maximum (in meters).

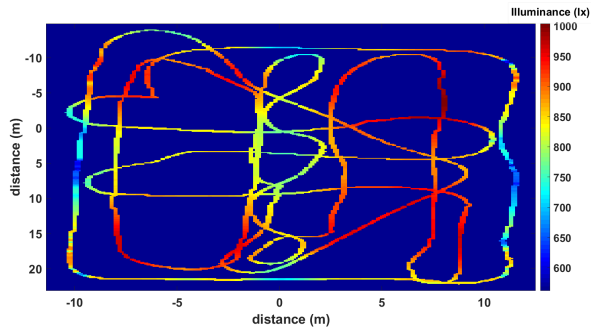
paths. In the first case, an external calibrated and accurate measurement system is required. Here we chose the second method consisting in cross comparison of different algorithms.

Results described in Figure 8 depict a maximal deviation between Lego and loam algorithms of 1.11m (at the end of the travel) with an average value of 0.71m (see Table 1). Comparing to the width (20 m) of the hall, it represents a

relative error of 3.5% which is quite acceptable and gives relative confidence in the illuminance map. This latter is constructed from the positions measured by Lego algorithm in Figure 9(a), then interpolated into a user-defined grid (every 10 cm in Figure 9)(b). For comparison, the recommended grid in the standards is made of points every 2 m. In the computed illuminance map (b), it can be seen the four lighting areas, which are consistent with on-site observations. The lights are adjustable halogens, of which this orientation was observed. The lighting level shall be

at least the Class III level, that is the average horizontal illuminance (E_{mean}) shall be over 300 lx for a uniformity ($E_{\text{min}}/E_{\text{mean}}$) of 0.7. We found an average illuminance of 854 lx and a uniformity of 0.66. It should be noted that this uniformity was altered by obtrusive light coming from windows located on one side of the hall. A fifty percent reduction in luminous flux would help to comply with the standard thresholds and save energy.

a) robot pathway.



b) illuminance map.

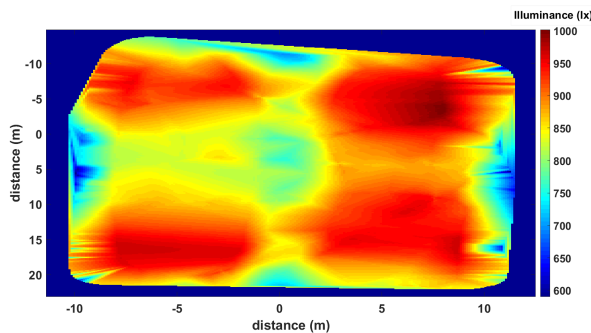


Figure 9: Generation of illuminance map.

3.2. Romulux scenario 2

This scenario took place in an international standard ice rink (see Figure 10(a)). Due to event broadcasting, it has to comply with lighting standards for television. The robot's motor skills were not affected by the ice, even though this was a concern at the outset. Figure 10(b) presents an example of recorded point-cloud. The lighting is intense and it is interesting to obtain a map of illumination to assess its homogeneity. For this ice hockey rink (namely Ice Park) at the international or national level of competition (class I), the standards recommend an average horizontal illuminance (E_{mean}) of 750 lx and a 0.7 uniformity ($E_{\text{min}}/E_{\text{mean}}$). The playing area measures 60m long by 30m wide. The recommended mesh-grid defined to achieve all the measurements contain 17 points in length and 9 points in width either 153 measurement points each separated by 3.5m. These measurements are made classically with an illuminance meter placed on the ground and moved successively on the 153 points of the mesh-grid. The advantage of using an automatic measurement system is then obvious.

a) The robot on the ice rink.



b) Point cloud of Ice Park.

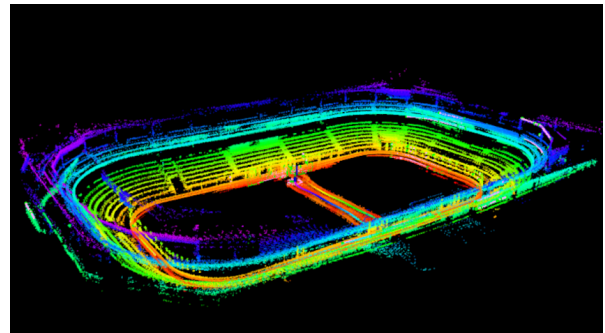


Figure 10: Romulux in Ice Park.

For this experiment, an IMU has been added to the robot to improve the SLAM algorithm robustification. The IMU is a MTi-610, which is the highest standard among Inertial Measurement Units⁸

The robot pathway (see Figure 11(a)) has been defined to maximize the measurement points into the mesh-grid and it took around 30 minutes to acquire (half a day would have been needed if doing the measurements manually). The Figure 11(b) shows the result of the generated illuminance map. It presents a maximum of illuminance at a corner corresponding to an entry on the ice rink. The average illuminance is found to be 3607 lx (for an objective of 750 lx, demonstrating the huge over-lighting). The minimal illuminance value is 2754 lx leading to an homogeneity of 0.76 (for an objective of 0.7). Again, a 75% reduction in luminous flux would still comply with standards and save energy.

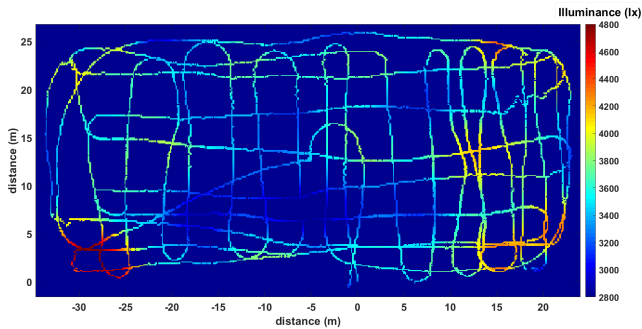
3.3. Strengths and limitations

Regarding those results, it appears that the presented robotic system can be a useful tool for illuminance mapping. It shows several advantages compared to classical processes:

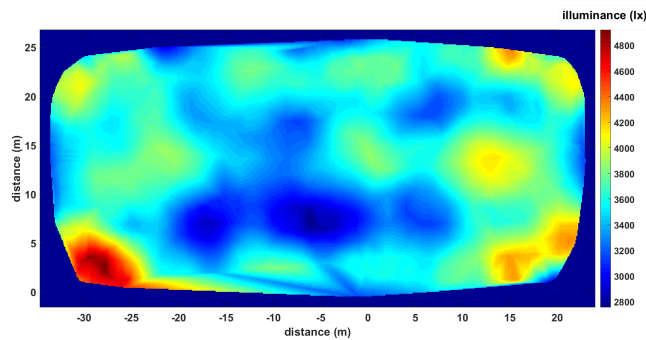
- Considerable time savings comparing to manual measurement. It takes about 30 minutes to cover 1000 m² with the robotic system where at least half a day is needed manually;

⁸<https://mtidocs.xsens.com/mti-600-series-user-manual>

a) robot pathway.



b) Ice Park illuminance map.


Figure 11: Generation of illuminance map.

- As the robot performs data acquisition when moving, it provides much more measurement than doing it by hand leading to a better space discretization;
- As the robot is tele-operated (up to 30 m) it removes illuminance measurement disturbance that can raise when an operator directly manipulates the sensor.

On the other hand, some limitations can be noticed at this state of the project:

- As the SLAM is not currently performed online, the robot is not fully autonomous yet;
- As the illuminance sensor has been calibrated, the light measurement uncertainties are precisely known however localization uncertainties are complex to estimate and are not evaluated so far, but will be the subject of a further work;
- The system is not user-friendly yet and must be operated by a specialist or at least after some training courses where manual measurements are more straightforward.

It should be noted that the presented system is still a prototype and has not been industrialized. It is custom-made and the hardware costs about 20 k€ including 7 k€ for the LiDAR and 4 k€ for the frame. Furthermore, maintenance costs that will raise when using the robot daily are not evaluated so far as it has only been considered for academic researches.

4. Conclusion and perspectives

This paper describes Romulux, a mobile robot equipped with a 3D LiDAR carrying an illuminance meter. A SLAM algorithm is used to estimate the robot location in an indoor environment in order to construct an illuminance map. Illuminance values can then be compared to the standards. As places are often over-lit, the comparison can lead to downward adjustment in lighting power, thus saving energy while maintaining a sufficient level of safety and comfort. The results are significant and can be replicated in different indoor environments. The first evolution will be to consider outdoor environment: in particular because requests have appeared for measurement campaigns on tramway lines and on outdoor sport facilities. The use of Romulux robot for outdoor applications pushes the limits of its design framework. Particular attention will be paid to the behavior of the robot and the results. To that purpose the robot will be equipped with a GNSS sensor. A second axis of study will be to evaluate the precision of the approach in order to guarantee the measurements and thus the illuminance map. It is needed to take into account the uncertainty of location, resulting from LiDAR precision and SLAM algorithm result. The problem is complex and interval analysis tools will be explored for solving it. A third axis of study will be the complete automation of the system, by integrating algorithms of explorations, and by automating the outputs, ideally by generating them in real time. Finally it can be noted that this approach could be extended with several sensor maps such as temperature, air quality.

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CRedit authorship contribution statement

Rémy Guyonneau: ROS programming and SLAM integration, experiments, redaction of the paper. **Franck Mercier:** mecatronic design and theoretical formalism, experiments, redaction of the paper. **Vincent Boucher:** illuminance map generation and standards comparisons, experiments, redaction of the paper.

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