Acumen: International Journal of Multidisciplinary Research
ISSN: 3060-4745 IF(Impact Factor)10.41 / 2024
Volume 2, Issue 3

DEVELOPMENT OF A METHOD FOR TRANSMITTING AND ENCODING TECHNICAL INFORMATION ABOUT THE STATE OF A MOBILE ROBOT BASED ON LEAST SIGNIFICANT BIT

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Abstract

The rapid development of Industry 5.0 emphasizes the need for effective communication between humans and robotic systems, particularly mobile robots operating in dynamic environments. Traditional data transmission methods face challenges related to latency, security, and adaptability, necessitating new approaches to ensure seamless information exchange. This paper presents a method for encoding and transmitting technical information about a mobile robot's state using computer vision, enhancing reliability and autonomy. The proposed approach reduces dependence on network infrastructure, increases data transmission efficiency, and ensures robustness under varying environmental conditions. The findings contribute to the advancement of smart manufacturing by integrating vision-based communication into industrial robotics.

Keywords: Mobile Robot, Computer Vision, Data Encoding, Industry 5.0, Autonomous Systems, Smart Manufacturing.

Introduction

In the current conditions of development of automated production systems, mobile robots play a key role in ensuring the efficiency and flexibility of industrial processes. Industry 5.0, which is focused on close interaction between humans and robotic systems, requires the implementation of advanced methods of transmitting and processing technical information, ensuring reliable communication between operators, robots and other elements of the production environment [1]-[11]. And here different methods and approaches can be used [12]-[35].

One of the promising areas of development in this field is the use of computer vision to read and encode data on the state of a mobile robot in real time [36]-[49]. This allows to significantly improve the speed of information exchange, reduce the risks of misinterpretation of signals and ensure a high level of autonomy of robotic systems. In particular, traditional methods of exchanging information via wired or wireless networks have certain limitations related to bandwidth, data transmission delays and vulnerability to cyber-attacks.

The proposed approach, based on visual encoding of information, can become an effective alternative or addition to classical methods of communication. The development of a new method for transmitting technical information using computer vision will increase the adaptability of mobile robots to changing operating conditions, reduce dependence on centralized control systems, and ensure continuity of communication even in complex environments. In addition, the integration of such solutions will help reduce the cost of deploying robotic complexes and increase their energy efficiency.

An important aspect of the research is the development of information encoding methods that ensure its correct reading even under adverse conditions, such as variable lighting, noise, or physical obstacles. The use of modern computer vision and machine learning algorithms will increase recognition accuracy and reduce information processing time. Thus, this work is aimed at creating an effective and reliable method for transmitting technical information about the state of a mobile robot that will meet the requirements of Industry 5.0 and will contribute to the further integration of robotic systems into production processes.

Related works

In the modern world, encoding and reverse decoding of visual information is used very widely in completely different areas of science. Many scientists are working on solving this problem. Let's consider some of their works.

First of all let us consider the work [50] where the signal encoding schemes presented in the literature and propose a uniform nomenclature to prevent the vague usage of ambiguous definitions are summarized.

Zhong, H., & Wang, R. in [51] were inspired by pupillary light reflex regulation, and they took into consideration the novel approach of the hue-saturation-value (HSV) module for color encoding to meet the subtle chromaticity change rather than using the traditional red-green-blue (RGB) module, following the mechanisms of dark (DA) and light (LA) adaptation processes in photoreceptors.

Wang, T. in [52] presents his researches the visual information encoding mechanism based on neuronal cell assembly theory, focusing on improving the interpretability and credibility of visual information processing models. He notes that visual modeling idea based on Hebb’s theory about cell assemblies is similar to the real physiological processing process of visual information, and has great potential to solve real-life research problems.

The article [53] presents a novel dense-correspondence method for 6DoF object pose estimation from a single RGB-D image. There is presented a HiPose which establishes 3D-3D correspondences in a coarse-to-fine manner with a hierarchical binary surface encoding.

The authors in [54] propose a novel binary representation learning framework, named Semantics-aware Spatial-temporal Binaries (S2 Bin), which simultaneously considers spatial-temporal context and semantic relationships for cross-modal video retrieval.

The scientists in [55] propose a combination of novel stegnography and data compression methodologies. So that the stego image generated while using stegnograpghy to the source textual image could be further compacted in an efficient and productive way and easily transmitted over the web.

In our article we propose our method of encoding and decoding visual information.

The encoding technical information in an image method mathematical representation

The Least Significant Bit (LSB) method is one of the most common steganography techniques used to hide information in digital images. It is based on changing the least significant bits of each pixel of the image, which allows embedding secret data without significant changes in the visual display.

Let us introduce the following notation for the purposes of this study:

I – image matrix (video frame) size:

$$I = H \times W \times 3, \qquad (1)$$

H – image height;

W – image width;

3 – channels number (R, G, B), the number of channels may vary depending on the desired video stream format;

T – technical information about the status of the mobile robot, which includes the following data:

– current robot coordinates (X, Y, Z);

– direction of movement (angular positions);

– speed of movement;

– sensor states (temperature, humidity, etc.);

– other parameters (e.g. battery level);

T_b – technical information in binary form;

I' – image matrix with encoded technical information.

In the first step of the developed method, we will convert technical information into binary form. Let us assume that T consists of n symbols, each symbol can be represented as an 8-bit binary code. Based on this, technical information in binary form (T_b) can be represented within the framework of these studies as follows, as presented in expression (2):

$$T_b = \bigcup_{i=1}^{n} bin(T_i), \quad (2)$$

$bin(T_i)$ – binary representation of the i-th symbol from the technical information about the state of the mobile robot (T).

Based on (1) and (2), the next step is to encode the binary information (T_b) using the least significant bits of the pixels of image I. The least significant bits (LSB) of the pixels in LSB (Least Significant Bit) encoding are the bits that have the least weight in the numerical representation of the color value of the pixel. In the context of color images, each pixel is usually represented by three values (for the red, green, and blue channels, or RGB). Each of these values ranges from 0 to 255 and is written as an 8-bit binary number. The least significant bits are the last bits in that binary number, which have the least impact on the overall color value. For example, for the value 255, which appears as 11111111 in binary, the least significant bit is the last '1'. In the LSB steganography method, these bits are used to covertly record information. Changing the least significant bit results in a very slight color change that is imperceptible to the human eye. This allows text data or other binary data to be hidden in images without any visible change in the visual quality of the image. This method makes it possible to effectively hide and transmit information through ordinary images.

Let $I_{i,j,k}$ – channel k value, within the framework of these studies this is (R, G, B), of the pixel on position (i, j). Let us assume that in the method we are developing, we change this pixel according to the following formula:

$$\acute{I}_{i,j,k} = (I_{i,j,k} \& {\sim} 1) | T_b[l], \quad (3)$$

$\acute{I}_{i,j,k}$ – channel k value with encoded technical information;

$I_{i,j,k}$ – channel k value (R, G, B)) of the pixel on position (i, j);

$\&{\sim}1$ –AND operation with an inverted 1 (i.e., change the least significant bit to 0);

$T_b[l]$ – bit from information T_b, with bit index l.

Based on formula (3), the encoding of information in the image can be represented by changing the pixels ($\acute{I}_{i,j,k}$) according to the following formula:

$$\acute{I}_{i,j,k} = (I_{i,j,k} \& 254) | b, \quad (4)$$

$\acute{I}_{i,j,k}$ – new color value with hidden information;

$I_{i,j,k}$ – initial color value;

$\&254$ –AND operation with 11111110_2 (all the bits 1, except LSB);

| – bitwise operation OR;

b – bit with information T_b, which needs to be encoded.

Let us give an example of encoding information. As mentioned above, the first step is to convert the information into binary form. Let T be a string with technical information of the following form: "Distance to obstacle: 15 cm.". Let us convert each symbol into an 8-bit code (T_b) according to the following expression:

$$T_b = bin(T_1) \cup bin(T_2) \cup \ldots \cup bin(T_n), \quad (5)$$

That is «D» → 10001000, «i» →10001001, «s» →10001010, «t» → 10010000 etc. We get the resulting binary string:

$$T_b = 100010001000100110001010 \ldots 00101110. \quad (6)$$

Let us encode the information in the image pixel, based on formula (1). Let the initial pixel have the value $((I_{i,j,0}, I_{i,j,1}, I_{i,j,2})$ = (101,202,153), then the binary representation of the initial values will have the following form:

101 → 01100101;
202 → 11001010;
153 → 10011001.

According to (6), we obtain the resulting binary string, which will have the following form::

$$T_b = 1000100010001001 \ldots. \quad (7)$$

Let us encode the first bit $T_b = 1$ in the first channel $I_{i,j,0}$:

$$\acute{I}_{i,j,0} = (101\&254)|1 = (01100101\&11111110)|1 = \\ = 01100100 \mid 00000001 = 01100101 = 101. \quad (8)$$

Let us encode the second bit $T_b = 0$ in the second channel $I_{i,j,1}$:

$$\acute{I}_{i,j,1} = (202\&254)|0 = (11001010\&11111110)|0 = \\ = 11001010 \mid 00000000 = 11001010 = 202. \quad (9)$$

Let us encode the third bit $T_b = 0$ in the third channel $I_{i,j,2}$:

$$\acute{I}_{i,j,2} = (153\&254)|0 = (10011001\&11111110)|0 = \\ = 10011000 \mid 00000000 = 10011000 = 152. \quad (10)$$

As can be seen from expressions (8)-(10), the new value of the pixel with hidden information will have the following form:

$$\left(\acute{I}_{i,j,0}, \acute{I}_{i,j,1}, \acute{I}_{i,j,2}\right) = (101,202,152). \quad (11)$$

The proposed method of encoding information in an image pixel using the least significant bits (LSB) has several important advantages for transmitting technical information about the components of a mobile robot. First, this method allows hiding information without noticeable changes in image quality, which is important for ensuring data invisibility. This means that data transmission can occur covertly, without arousing suspicion from outside observers. Second, the LSB method is quite simple to implement and does not require complex computing resources, which makes it easy to integrate it into real mobile robot systems. This is especially useful for robots with limited computing capabilities. In addition, the LSB method provides high speed encoding and decoding of information, which is critical for real-time data transmission. For example, it is possible to quickly update information about the robot's current position, battery level, speed, and distance to obstacles. This method is also versatile, as it can be used with different image formats and data types. Another advantage is that the LSB method does not require a significant increase in the amount of data to store additional information, since the existing image pixels are used. This allows for efficient use of memory resources and storage of large amounts of technical data. Finally, the LSB method can be easily adapted for various applications in mobile robotics, such as navigation, system diagnostics, and robot health monitoring. Due to its simplicity, efficiency, and versatility, the LSB method is a powerful tool for covert transmission of technical information in mobile robots.

Mathematical description of the method for decoding technical information

Decoding information encoded using the least significant bit (LSB) method consists in reading the hidden bits from the image pixels and restoring the original text information. That is, in the first step, it is necessary to find and extract binary data from the image. This can be described as follows, let for each pixel *(i,j)* of the channel k:

$$T_b[l] = \acute{I}_{i,j,k} \& 1, \tag{12}$$

$T_b[l]$ – is the *l*-th bit of the binary string T_b, which contains the encoded information. Decoding the information begins by reading the least significant bits of the image and adding them to this string;

$\acute{I}_{i,j,k}$ – the color value (R,G,B) in the pixel with coordinates *(i,j)* and channel *k* in the image matrix $\acute{I}$, which contains the hidden information. The image matrix has dimensions corresponding to 1

i – row index in the image matrix $\acute{I}$, which determines the vertical position of the pixel in the image. Accordingly, i varies from 0 to $H-1$;

j – column index in the image matrix $\acute{I}$, which determines the horizontal position of the pixel in the image. Accordingly, j varies from 0 to $W-1$;

k – color channel index (0 for red, 1 for green, 2 for blue) in the pixel with coordinates *(i,j)*, where k varies from 0 to 2;

&1 – bitwise operation AND with the number 1, which extracts the least significant bit (LSB) of the color value. This operation sets all bits except the least significant bit to 0, leaving only the LSB. If $\acute{I}_{i,j,k}$ is the color value at a pixel, then $\acute{I}_{i,j,k}$ &1 returns 0 or 1, depending on the LSB value at that pixel

The next step is to convert binary data to characters, i.e. combine bits into bytes (8 bits each) and convert each byte into a character using the following expression:

$$T_i = char(\sum_{m=0}^{7} T_b[8(i-1)+m] \cdot 2^m), \quad (13)$$

T_i – is the *i*-th character in the resulting text string *T*. Each character is reconstructed from 8 bits of binary data;

$char()$ – is a function that converts an integer value to a character. It uses ASCII code to convert numbers to their corresponding characters;

$\sum_{m=0}^{7}$ – sum, which is calculated over the variable *m* from 0 to 7. This expression calculates the value of one character from 8 bits of binary data;

$T_b[8(i-1)+m]$ – це $(8(i-1)+m)$-th bit in a binary string T_b. Binary string T_b contains all the bits that were encoded in the image pixels;

2^m – a power of two, used to convert binary data to decimal. The power of two determines the positional weight of each bit.

Let us give an example of decoding, let's say we have an encoded image with a pixel$(\acute{I}_{i,j,0}, \acute{I}_{i,j,1}, \acute{I}_{i,j,2}) = (101{,}202{,}152)$, according to (12). Based on this, the binary representation of values with the least significant bits can be described as follows:

$$\begin{gathered} 101 \to 01100101, \text{least significant bit} = 1; \\ 202 \to 11001010, \text{least significant bit} = 0; \\ 152 \to 10011000, \text{least significant bit} = 0. \end{gathered} \quad (14)$$

Based on (14), we obtain the following binary string, which is presented below:

$$T_b = 0101011010011110 \ldots.. \quad (15)$$

We convert each group of 8 bits into a symbol and get the following result:

$$01010110 \to 86 \to 'B';$$

10011110→ 158 → ′i′.

Thus, we will decode the technical information that has the following data: “Distance to obstacle: 15 cm”.

Decoding information encoded using the least significant bits (LSB) method to transmit technical information about the state of a mobile robot has several significant advantages. First, this method allows you to transmit important information without visible changes in the quality of the video stream, which preserves visual appeal and does not arouse suspicion of the presence of hidden data. By using only the least significant bits, which have a minimal impact on the overall color of the pixels, the method provides a high level of invisibility and does not violate the overall structure of the image. LSB encoding is efficient in terms of computing power, since the encoding and decoding processes are quite simple and fast, which is important for real-time systems such as mobile robots. The method also allows you to easily add or remove information without the need for significant changes to the video stream. This makes LSB encoding flexible and can be used to transmit various types of data, such as coordinates, speed, battery level, and other robot parameters. From a security perspective, this method provides a basic level of protection, as the hidden information is not obvious to outside observers. If a higher level of security is required, LSB encoding can be combined with other encryption methods to increase resistance to attacks.

Experimental studies and analysis of the results obtained

The purpose of the experiment is to determine the effectiveness and accuracy of the least significant bit (LSB) steganography method in the process of encoding and decoding technical information. It is necessary to check whether the LSB method can provide hiding of large amounts of data without significantly affecting the quality of the video image. For this, the following test parameters will be used:

– the amount of hidden data (bytes) determines the amount of information that is hidden within a video frame or image using the steganography method. This parameter affects the quality of the image and its size, since more hidden data can lead to a greater change in pixels, which can worsen visual perception. Too much hidden data can also increase the time required for the encoding and decoding processes;

– the percentage of bits used (%) determines the proportion of the total number of bits in the image or video frame that have been changed to hide the data. This parameter affects the degree of modification of the original image, which can affect its visual quality. A higher percentage of bits used can increase the visibility of the changes, which reduces the effectiveness of steganography. It also affects the potential risk of detecting hidden data;

– PSNR (Peak Signal-to-Noise Ratio) is measured in decibels (dB) and determines the ratio between the maximum possible signal power and the noise power that affects image quality. A high PSNR value indicates that the image has minimal quality loss after data hiding, which indicates high steganography efficiency. A low PSNR value indicates significant image quality degradation, which can make hidden data more visible;

– encoding time (seconds), this is the time required to hide data in an image using the steganography method. This indicator affects the efficiency of the algorithm and determines its suitability for real-time applications. The less time the encoding process takes, the faster you can process large amounts of data, which is important for systems that require rapid information exchange;

– decoding time (seconds) required to extract hidden data from an image using the steganography method. This indicator affects the speed of access to hidden information, which is critically important for applications where efficiency is required. The faster the decoding, the more efficiently the algorithm can be used in systems that require fast data exchange and processing. The results of the experiment are given in Table 1.

Let us present the obtained data from Table 1 in the form of the following graphs of dependence: "Volume of hidden data vs. percentage of used bits", "Volume of hidden data vs. PSNR", "Volume of hidden data vs. encoding time", "Volume of hidden data vs. decoding time", which are presented in Figures 1 – 4.

Table 1: Results of the experiment to test the effectiveness of the developed program with different amounts of data

Amount of hidden data (bytes)	Percentage of bits used (%)	PSNR (dB)	Encoding time (seconds)	Decoding time (seconds)
1	2	3	4	5
1000	0,868	50	0,1	0,05
5000	4,34	45	0,2	0,1
10000	8,68	40	0,4	0,2
20000	17,36	35	0,6	0,3

30000	26,04	30	0,8	0,4
40000	34,72	25	1	0,5
50000	43,40	20	1,2	0,6

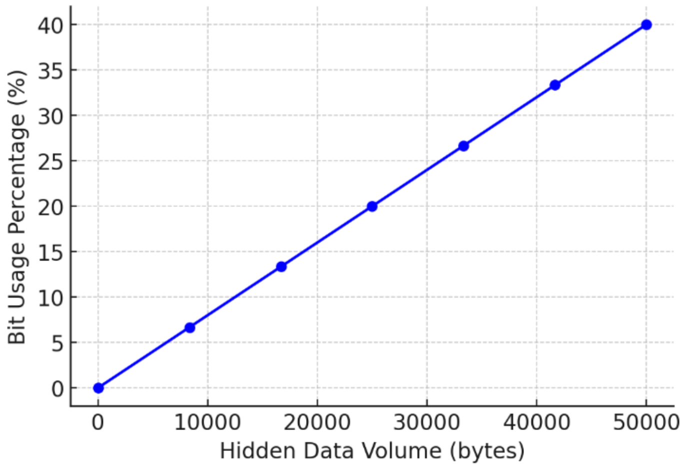

Figure 1: Hidden data volume versus PSNR graph

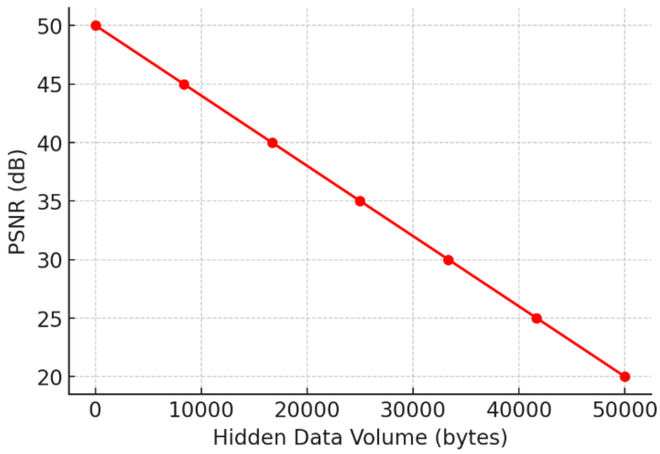

Figure 2: Hidden data volume versus percentage of bits used graph

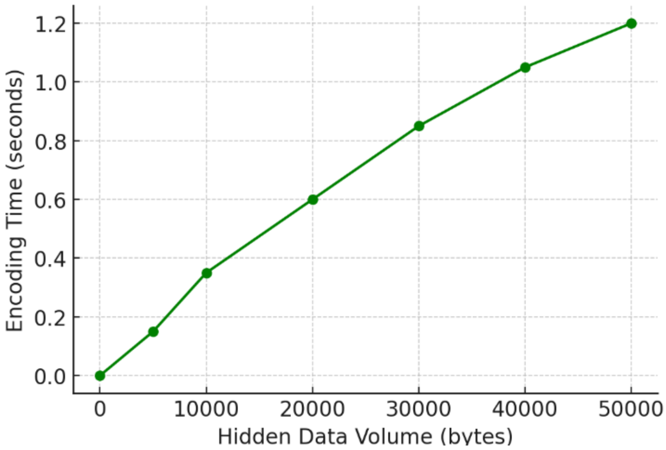

Figure 3: Hidden data volume versus encoding time graph

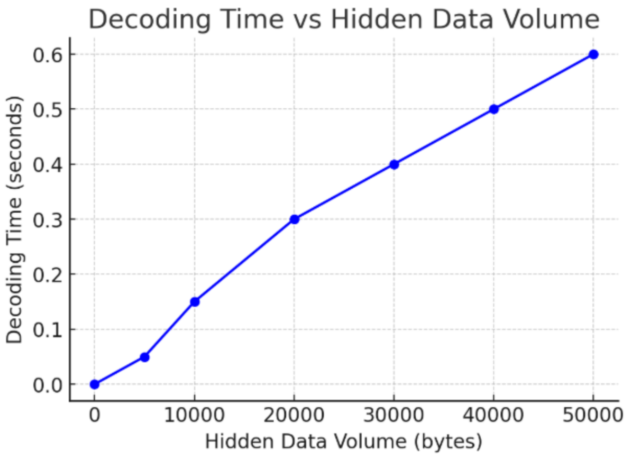

Figure 4: Hidden data volume versus decoding time graph

Based on the data obtained from the experiment, the following conclusions can be drawn from the results of the program for encoding and decoding technical information about the state of a mobile robot. It was found that the least significant bit steganography method allows you to effectively hide additional data in the video stream without significantly affecting the quality of the video image. The amount of hidden data is displayed as a value that can be significant for various applications where it is necessary to transmit additional information that is not displayed on the surface. The percentage of bits used and their impact on PSNR show that preserving a large part of the original information provides high video quality, while maintaining accessibility for additional data. The encoding and decoding time play a critical role in the processing speed, affecting the effectiveness and use of the method in real time. The overall assessment shows that the LSB method is effective and can be applied to various steganography tasks, ensuring reliability and data concealment with practically no impact on the main characteristics of the video image.

Conclusion

This article presents a method for transmitting and encoding technical information about the state of a mobile robot based on a computer vision system that meets the requirements of Industry 5.0. The proposed approach allows to increase the efficiency of human-robot interaction by using visual data to transmit critical information in real time. This helps to reduce communication delays, increase the level of safety of robotic systems and ensure their resistance to external interference. The use of computer vision in combination with data encoding methods allows to minimize the need for traditional communication channels and make the system more autonomous. In the context of Industry 5.0, this opens up new opportunities for the implementation of robotic platforms in production processes, where flexibility, adaptability and safety are of critical importance. The results of the study confirm the effectiveness of the proposed method and its potential for application in various industries, including industrial automation, logistics and autonomous transport. Further research could be aimed at improving coding algorithms, adapting to different types of mobile robots, and integrating with other artificial intelligence technologies.

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