3D Laser Scanner for Tele-exploration Robotic Systems

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***Abstract*— Much work has been done on the development of sophisticated sensors for mobile robotics but in the field of tele-exploration simple camera based systems are dominating. Therefore we developed a continuous rotating 3D laser scanner with a camera which fits the requirements of this field very well. Due to its design concept it is easy to integrate on many mobile robot systems and has less requirements to the computing hardware. Furthermore we implemented different data processing algorithms to support the navigation task of the operator.**

I. Introduction

Mobile robotic systems for tele-exploration are gaining more and more importance, not only for explosive ordinance disposal (EOD) but also for, e.g., industrial inspection tasks and rescue operations. For many of those applications, fully autonomous systems are not applicable because of safety- or efficiency reasons. Even though much work has been done on developing sophisticated sensors for mobile robots, today's commercial available tele-exploration systems are strongly focused on mobility and robustness but still do not provide much more visual feedback to the operator than cameras alone. This lack of commercial development may be driven by high development costs and insufficient robustness of current sensor systems. One major problem is the missing spatial information of the system and its environment. Needless to say, that for manipulating dangerous objects or navigating in collapse endangered scenarios, spatial information will improve the performance of the system and its operator. At the moment laser scanner based systems seem to be the most promising technology to provide these information. A well designed continuous rotating 3D laser scanner was developed by the Real Time Systems Group of the University of Hannover [17] and is used for mobile robotic systems and industrial applications. This sensor is highly integrated and based on an embedded PC with a real-time linux operating system for sensor control and data preprocessing. Based on the principles of this sensor we developed a new 3D laser scanner which fits the requirements of tele-exploration robotic systems well while keeping the integration effort low and providing an open architecture. This is achieved by using standard interfaces and technology which is common on today's tele-exploration systems. In addition, we combined this 3D laser scanner with a camera system to provide optimal operator assistance. The reasons why this sensor is interesting for tele-exploration applications are:

- Easy to integrate on tele-exploration robotic systems
- Open architecture for customer-specific extensions
- Less requirements on the computation hardware
- Operating System independent
- Good cost-value ratio

The remaining paper is structured as follows: The next sub-sections present the state-of-the-art in tele-exploration robotics and three-dimensional mapping of environments. Section II describes the robot platform Kurt3D, the design of the new continuous rotating 3D laser scanner and explains the motivation for choosing this configuration. In section III different data processing algorithms for operator assistance are presented and finally the paper is concluded and an outlook of future work is given.

Fig. 1. The tele-exploration robot platform Kurt3D. Left: The six wheel platform with two pan-tilt cameras, illumination and Pentium Notebook. Right: The continuous rotating 3D laser scanner which is based on a standard 2D Laser Range Finder, a SICK LMS200. On top of the scanner a camera is mounted which creates a surround view of the scanned environment.

A. Robotic Systems for Tele-exploration – State of the Art

Most of the today's commercially available robot systems for tele-exploration are designed for the inspection of structural damages, hazardous material or EOD [2], [12]. They are designed for high mobility to handle rough terrain but the sensory equipment is mostly limited to several cameras which are distributed over the system. The EOD robotic system teleMax, developed by Telerob (cf. fig. 2), for example is a four-track driven robot, equipped with a 7 DOF manipulator and 3 cameras, one front, one back and one manipulator camera [2]. The camera images are transmitted by a wireless connection at 2,4 GHz to the operator desk and the control commands by a 433 MHz wireless connection.

A similar systems is the PackBot [1] from iRobots (cf. fig. 2). It is also a four-track system but with a different track setup (cf. fig. 2) and it is intended to be carried by one person only. It is available in three configurations which differ in the on-board equipment. The first uses fixed mounted cameras and microphones, the second provides a setup where these sensors are mounted on a pan-tilt unit, and finally the third system - PackBot EOD - is additionally equipped with an omni-reach manipulator.

Other robot systems are designed for the examination of small tubes and corridors or cavities in rubble that maybe would be quicker to excavate but would endanger other people or infrastructure. They are designed to go a bit deeper than traditional search equipment, i.e, cameras mounted on poles [12]. For example the micro-tracs "micro-VGTV" and "Solem" [13], are small tank-tracked vehicles that are connected to the operator by wire for transmitting a video signal. The operating range of those systems typically is $5 - 20$ m,

All these systems have in common that cameras are the main sensors for operator assistance in the navigation or manipulation task. Therefore mapping of the environment is basically not possible and navigation and obstacle avoidance has to be done based on the two dimensional camera images only.

Fig. 2. Left: The teleMax robot system from teleRob [2]. Equipped with a 7 DOF manipulator and 3 cameras. The flippable four-track drive ensures maximum mobility. Right: The PackBot EOD system from iRobot [1]. Also a flippable four track drive but with another setup. Designed to be carried by one person only and equipped with a manipulator and cameras.

B. Environment Mapping in 3D – State of the Art

In the context of tele-exploration, 3D data primarily seem to be very useful for safe navigation of the robot in unknown environment. Nevertheless in the case of exploring collapsed buildings or very large areas it is useful to generate a map of the explored area to guide human rescue teams. Especially for collapsed buildings, it is desirable to generate these maps three-dimensional. In the robotics community this is called "Simultaneous Localization and Mapping – SLAM" and is a very large field of research with many different groups involved.

A few groups are using 3D laser scanners directly [5], [8], [16], [21], [22]. The RESOLV project aimed to model interiors for virtual reality and tele presence [16]. They used a RIEGL laser range finder on robots and the ICP algorithm for scan matching [7]. The AVENUE project developed a robot for modeling urban environments [5], using an expensive CYRAX laser scanner and a feature-based scan matching approach for registration of the 3D scans in a common coordinate system. Nevertheless, in their recent work they do not use data of the laser scanner in the robot control architecture for localization [8]. Triebel et al. uses a SICK scanner on a 4 DOF robotic arm mounted on a *B21r* platform to explore the environment [21].

Instead of using 3D scanners, which yield consistent 3D scans in the first place, some groups have attempted to build 3D volumetric representations of environments with 2D laser range finders [9], [20], [22]. Thrun et al. [9], [20] use two 2D laser range finder for acquiring 3D data. One laser scanner is mounted horizontally, the other vertically. The latter one grabs a vertical scan line which is transformed into 3D points based on the current robot pose. The horizontal scanner is used to compute the robot pose. The precision of 3D data points depends on that pose and on the precision of the scanner. Howard et al. uses the restriction of flat ground and structured environments [10]. Wulf et al. let the scanner rotate around the vertical axis. They acquire 3D data while moving, thus the quality of the resulting map crucial depends on the pose estimate that is given by inertial sensors, i.e., gyros [22]. In this paper we let rotate the scanner continuously around its vertical axis, but accomplish the 3D mapping in a stop-scan-go fashion, therefore acquiring consistent 3D scans as well.

II. THE TELE-EXPLORATION PLATFORM KURT3D

Kurt3D (fig. 1) is a mobile robot platform with a size of 45 cm (length) $\times$ 33 cm (width) $\times$ 26 cm (height) and a weight of about 15.6 kg, an indoor as well as an outdoor version exist [3]. Two 90 W motors are used to power the 6 wheels. In comparison to the original Kurt3D robot platform, the outdoor version has larger wheels, where the middle ones are shifted outwards. This yields a larger ground clearance and a track-like utilization of the wheels. To enhance on-the-spot turning performance for high friction floors the front and rear wheels have no tread pattern. The main processing unit of the robot is an Intel-Centrino-1400 MHz with 768 MB RAM and a Linux operating system which is connected to the embedded 16-Bit CMOS micro-controller, used to process the low level commands to the motor, via a standard CAN interface. Kurt3D operates for about 4 hours with one battery charge (28 NiMH cells, capacity: 4500 mAh).

Depending on the scenario, Kurt3D can be equipped with a pitching 3D laser scanner [18] or the new developed continuous rotating 3D laser scanner and camera combination, which will be described in more detail in section II-B.

Furthermore there are two front cameras, mounted on pan-tilt-units. For operating even in dark environments 2×4 super bright LEDs and two fluorescent tubes are used to illuminate the surroundings. The LEDs are directly attached to the two front cameras. Additional 8 NiMH cells are used to power the light.

A. 3D Laser Scanning Methods for Tele-exploration Robotics

A common way for building a 3D laser scanner for robotics applications is to use a standard 2D laser range finder (LRF), e.g. a SICK LMS 200, and add another axis to reach the third dimension. In [23] Wulf et al. analyzed different possible configurations of those system. They distinguished four different types, namely the *pitching scan, rolling scan, yawing scan and yawing scan top*. The original Kurt3D platform is equipped with a *pitching scan* system, where the 2D LRF builds a horizontal scan plane and is pitching up and down [18]. Our experience, especially gained in several RoboCup Rescue [15] competitions, has shown that for tele-exploration applications the *yawing scan* method is also very applicable. Here the 2D LRF builds a vertical scan plane and is continuous rotating around the vertical axis. A major advantage in comparison to other configurations is the 360° view of the environment, since it simplifies the operator tasks. The operator receives three-dimensional information of the robot's environment which allows safe navigation and better orientation in unknown and cluttered environments. A *pitching scan* device is normally used in a stop and go manner whereas the continuous rotation scanner acquires data continuously. Another advantage is the fact that here the LRF device is not accelerated or decelerated for each scan which on the one hand is less stressing for the mechanics and on the other hand is reducing the power consumption per scan.

In the joined RoboCup Rescue Team "Deutschland 1" [19] in 2005 we used a 3D laser scanner, developed by the Real Time Systems Group of the University of Hannover [17]. This device is a highly integrated 3D sensor and includes an embedded PC for sensor control and data preprocessing. Since the system is using a real-time operating system, it is possible to acquire 3D data with high temporal and therefore also spatial precision. This allows acquisition of consistent scans while moving the sensor, presuming correct pose information. They have shown that this sensor can also used for other applications like region surveillance in industrial environments.

Inspired by these sensor we developed a continuous rotating 3D laser scanner 1 which is technically simpler and less expensive, but nevertheless fulfills the requirements for tele-exploration applications. Due to its design concept it is easy to integrate on many mobile robot systems and it is even less expensive than many other, very common 3D laser scanning system for mobile robotics. Another important feature is the camera which is attached to the continuous rotating scanner and which delivers 360° color images of the environment at the same time. The next section describes this sensor in more detail.

B. The Continuous Rotating 3D-Laser-Scanner and Camera Combination

The continuous rotating 3D laser scanner is based on a SICK LMS 200, a 2D LRF with an aperture angle of 180° and three different resolutions, i.e., 180, 360 or 720 scan points. The data interface is a serial RS422 connection with a maximum bandwidth of 500k baud. This LRF is mounted vertically on a dc-motor based drive mechanism to build a *yaw scanning device* (cf. fig. 1. On top of the rotating scanner a standard low cost USB camera is mounted, a Logitech Quickcam 4000 pro with 640×480 pixel resolution and a maximum frame rate of 15 fps with full resolution (30 fps for 320×240 pixel). To realize the continuous rotation of the 2D LRF and the camera, the data- as well as the power connections are routed over a package of slip rings. For the drive unit a standard 24V dc motor with optical wheel encoder is used. Those encoders are very often used for driving mobile robots, e.g., in Kurt3D [3]. For those robots, it is possible to utilize the same interface and hardware driver for controlling the sensor drive unit as it is used already for controlling the robot drive and therefore reduces the integration effort. Here we are using a TMC200 [4], a three channel motor controller board with serial RS232 interface.q

For generating oriented 3D environment scans it is necessary to initialize the starting position for the rotating sensor. Since the optical encoder is a relative position sensor, some other reference has to be found. Steckmann et al. [17] are using an additional sensor for determining the starting position. We explicitly do not use such a sensor to avoid the need of an extra input interface to the control software and so keeping the integration effort on a low level. Instead of this, a software-sensor is used. In the starting routine of the sensor, at maximum 1 initialization turn of the sensor is required. During this turn, the single 2D scan planes are analyzed for a specific and predefined pattern which is very close to the sensor and belongs to the mount of the drive unit. The accuracy of this procedure depends on the scanning frequency of the 2D LRF and the actual rotation speed of the sensor. For example: A 180 point 2D scan takes 13,3 ms and the sensor needs 4,8 seconds for a rotation of 360° . So the accuracy of the initialization is 1° . This is less accurate than using hardware sensor based method but is sufficient for the application of tele-exploration robotics. Once this starting position is determined the 3D data generation is done by using the position information of the optical encoders. The turning speed of the sensor is stable since it is controlled by a PID controller, integrated in the TMC motor controller, and the timing of the SICK LMS 200 is very precise which allows to distribute the acquired 2D scans uniformly over a full rotation. The resolution of the 3D laser scanner can be influenced by the turning speed of the sensor and the scanning mode of the 2D LRF. Running the scanner in the 180 scan point mode and rotating with a speed of 4,8 seconds per turn gives a vertical and horizontal resolution of 1° .

In the current configuration the rotating 3D laser scanner is combined with an USB camera, which is used for acquiring 360° surround view images. Several images are taken on each rotation of the sensor and concatenated to a single large image. The camera provides an aperture angle of 45° , which means that for covering a 360° view eight images are required. If the camera is initialized with 10 frames per second and the laser scanner has a rotation period of 4.8s, then every 6th image is taken to create the large image. In this version, the images are concatenated without any alignment methods which sometimes yields to visible transitions in the image.

III. Operator Assitance

A. Navigation based on 3D Environment Data

Our experience in the field of tele-exploration robotics shows that it is very difficult or even impossible to navigate safe in cluttered and unknown environments by using only front cameras which gives a robots perspective. Especially in narrow passages it is very useful to see the robot and its environment at the same time. Some groups generated that capability by mounting a camera on a pole or manipulator positioned to provide a bird's-eye-view of the scene. A more sophisticated solution is to use information from a 3D laser scanner, since it gives the real spatial properties and therefore improves collision free navigation. One problem here is how to present this three-dimensional information to the operator. Projecting all 3D data points into a plane to get a top-view of the scene would not give useful information to the operator as one can see in fig. 3. Some kind of data preprocessing has to be done.

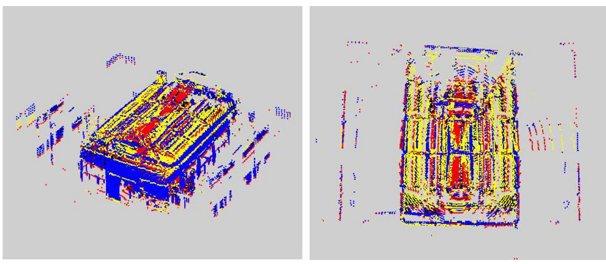

Fig. 3. A 3D laser scan of the Fraunhofer AIS Robotics Pavillon. On the right side all 3D information are projected to the X-Y plane. To extract information about the structure of the building or the interior further data processing is essential.

The acquired 3D point cloud is raw sensor data and includes many data points for the floor as well as for the ceiling. Needless to say, that it is not possible to distinguish between those points and obstacles in a top-view representation. Therefore we implemented two different methods for preprocessing the 3D data, the *Virtual 2D Scans*. This concept was originally developed by Wulf et al. [22] and there utilized for a line based SLAM algorithm.

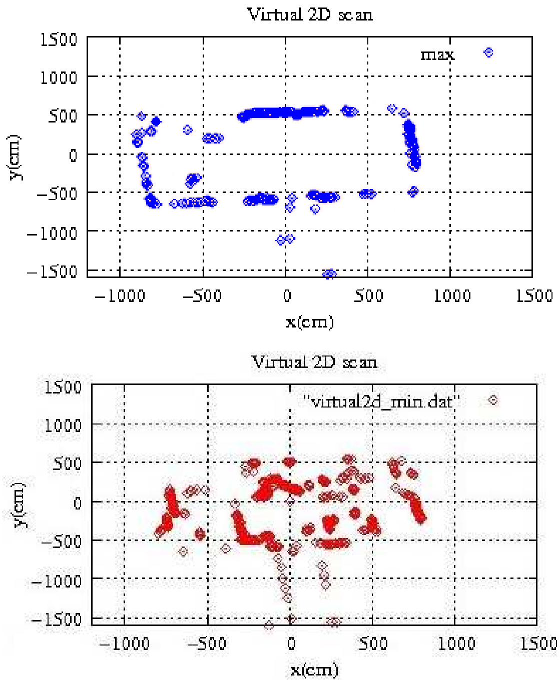

Fig. 4. Virtual 2D Scans, based on the original data shown in fig. 3 Upper Image: The Virtual 2D Scan - Maximum. For each vertical 2D scan the point with the largest distance is extracted. This yields representation which gives the boundaries of the environment, here the walls. Lower Image: The Virtual 2D Scan Minimum. This representation gives the obstacles of the environment. Therefore the closest point for each vertical 2D scan is extracted. To exclude the ceiling and the floor, only 3D data from, e.g. 10 cm up to 1 m are considered.

1) The Virtual 2D Scan - Maximum: This method is filtering the 3D point cloud for the boundaries of the environment, e.g., the walls for indoor environments. Here all scan points are projected onto the X-Y plane by setting the Z-value to zero (cf. fig. 3). Next for each original 2D scan (from 0° to 359°) the point with the largest distance to the sensors center of rotation is chosen and all other points are removed. This yields to a representation where the floor, the ceiling and the interior is removed, which is shown in figure 4, upper image. With this method regions with doors, windows or other larger openings are not considered as walls or boundaries. For the operator this representation is useful for large area navigation, orientation and more global path planning.

2) The Virtual 2D Scan - Minimum: In contrast to the previous method, here the close-up range of the robot system is of interest. The procedure is similar, but instead of searching the point with the largest distance for each vertical 2D scan, the closest point is sought. If one would use the X-Y plane projection of all points, the floor and the ceiling would cause obstacles all around the robot, since they are the closest points. Therefore the projection is limited from the height at which obstacles are still traversable for the robot up to the height of the robot. This gives the closest objects to the robot which would collide with the robot and thus supports the operator avoiding collisions even in very narrow passages. A *Virtual 2D Scan - Minimum* from the original 3D point cloud of figure 3 is shown in figure 4, lower image. For almost empty rooms, the results of both methods is very similar.

B. Navigation Assistance using 360° Images

As already described in section II-B the 3D laser scanner is combined with a USB camera to acquire surround view images on each turn of the scanner. Since the *Virtual 2D Scans* only provide spatial data, additional information from camera images are provided to the operator. This is required if a movable object, e.g., a curtain, is obstructing a passage. In the 3D laser scanner data a wall and a curtain are not distinguishable. For providing an optimal surround view to the operator, the whole image is split into a front and a back view. The operator is therefore always able to classify obstacles which are shown in the *Virtual 2D Scans*. Because of the camera rotation and its exposure time, the images are a little bit distorted but still much better than, e.g., images from omni-direcitonal cameras. Since these images are intended for providing just an overview, another camera is recommended for inspection purposes, at the best mounted on a pan-tilt unit.

Fig. 5. A sample image of the surround view, acquired with the USB camera attached to the continuous rotating 3D laser scanner. Upper part: The front view, from -90° to +90° . Lower part: The back view, from +90° to +270° .

C. Mapping and Relocalisation

For exploring large areas or for example collapsed buildings as advance guards for human rescue teams, it is highly desirable to create a 3D map as precise as possible during the mission. In contrast to the navigation assistance task from the previous section, where the 3D data are captured continuously while the robot is moving, here it is recommended to use the 3D laser scanner in a stop-and-go manner to improve the quality of the resulting map. To avoid occlusions in the 3D data of the map, multiple scans are necessary. All these scans have to be merged into a single coordinate system to create a correct and consistent model. This process is called registration. If the localization of the robot with the 3D laser scanner were precise, the registration could be done directly based on the robot pose. However, due to the imprecise robot sensors, self localization is erroneous, so the geometric structure of overlapping 3D scans has to be considered for registration. Furthermore, robot motion on natural surfaces has to cope with yaw, pitch and roll angles, turning pose estimation into a problem in six mathematical dimensions. A fast variant of the ICP algorithm registers the 3D scans in a common coordinate system and relocalizes the robot. The basic algorithm was invented in 1992 and can be found, e.g., in [7].

Given two independently acquired sets of 3D points, M (model set, $|M| = N_m$) and D (data set, $|D| = N_d$) which correspond to a single shape, we aim to find the transformation consisting of a rotation $\boldsymbol{R}$ and a translation $\boldsymbol{t}$ which minimizes the following cost function:

$$E(\boldsymbol{R}, \boldsymbol{t}) = \sum_{i=1}^{N_m} \sum_{j=1}^{N_d} w_{i,j} \left|\left|\boldsymbol{m}_i - (\boldsymbol{R}\boldsymbol{d}_j + \boldsymbol{t})\right|\right|^2 . \quad (1)$$

$w_{i,j}$ is assigned 1 if the i-th point of M describes the same point in space as the j-th point of D. Otherwise $w_{i,j}$ is 0. Two things have to be calculated: First, the corresponding points, and second, the transformation ($\boldsymbol{R}$, $\boldsymbol{t}$) that minimize $E(\boldsymbol{R}, \boldsymbol{t})$ on the base of the corresponding points. The ICP algorithm calculates iteratively the point correspondences. In each iteration step, the algorithm selects the closest points as correspondences and calculates the transformation $(\boldsymbol{R}, \boldsymbol{t})$ for minimizing equation (1). The assumption is that in the last iteration step the point correspondences are correct. Besl et al. prove that the method terminates in a minimum [7]. However, this theorem does not hold in our case, since we use a maximum tolerable distance d_{max} for associating the scan data. Here d_{max} is set to 15 cm for the first 15 iterations and then this threshold is lowered to 5 cm. Fig. 6 (left) shows two 3D scans aligned only according to the error-prone odometry-based pose estimation. The point pairs are marked by a line.

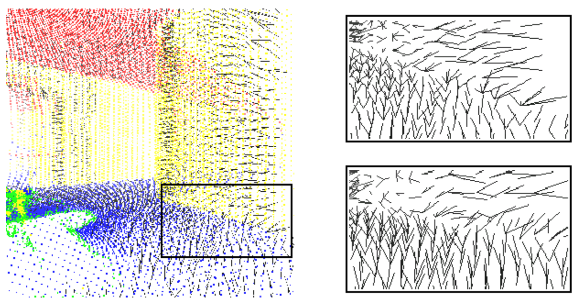

Fig. 6. Point pairs for the ICP scan matching algorithm. The left image show parts of two 3D scans and the closest point pairs as black lines. The right images show the point pairs in case of semantically based matching (top) whereas the bottom part shows the distribution with closest points without taking the semantic point type into account.

1) Computing the Optimal Rotation and Translation in 6D: In every iteration the optimal transformation ($\boldsymbol{R}$, $\boldsymbol{t}$) has to be computed. In earlier work [14] we used a quaternion based method [7], but now we are using a method which is based on singular value decomposition (SVD), because it is robust and easy to implement. It was first published by Arun, Huang and Blostein [6] in 1987 and a more detailed description of our implementation can be found in [19].

2) Computing Point Correspondences: As mentioned earlier, the strategy of ICP is to always use closest points. To speed up computation, kd-trees have been proposed [7]. For searching points we use optimized, approximate kd-tree.

In [19] we presented a method which utilizes semantic knowledge to speed up the ICP matching algorithm and yields to a more robust scan matching. Therefore a forest of kd-trees is used to search the point correspondences. For every semantic label a separate search kd-tree is created. The algorithm computes point correspondences according to the label. For example, points which belonging to the wall are paired with wall points of previous 3D scans. Using semantic information helps to identify the correct correspondences, thus the number of ICP iterations for reaching a minimum is reduced. In addition, maximizing the number of correct point pairs guides the ICP algorithm to the correct (local) minimum leading to a more robost algorithm.

IV. Conclusion and Future Work

This paper has presented our new continuous rotating 3D laser scanner which very well fits the requirements of sensors for tele-exploration robotic systems. Because of the continuous 360° spatial information, the operator is able to naivgate safe and reliable even in cluttered and endangered environments. To povide this assistance two different versions of *Virtual 2D Scans* have been implemented, whereof one filters the 3D laser scans for the boundaries of the environment, the walls and the other one for the obstacles. Furthermore our system includes a 360° camera which is attached on top of the rotating 3D laser scanner. This enables the operator to classify obstacles which are showing up in the *Virtual 2D Scans*. A complete camera surround view is updated with the same rate as the laser scans are.

Aim of the future work is to develop visualization methods which allow the operator to see the information of the 3D laser scanner and the surround view camera as a single integrated image. Right now these are two different images and one has to switch from one to the other. Another point is the concatenation of the camera images. On the one hand, the merging of the images should be supported by some feature based matching algorithm like. e.g., SIFT [11] and on the other hand a deconvolution algorithm, which corrects distortion caused by the camera rotation would yield to better images.

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