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An Adaptive Connectivity-based Centroid Algorithm for Node Positioning in Wireless Sensor Networks

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Abstract

In wireless sensor network applications, the position of nodes is randomly distributed following the contour of the observation area. A simple solution without any measurement tools is provided by range-free method. However, this method yields the coarse estimating position of the nodes. In this paper, we propose Adaptive Connectivity-based (ACC) algorithm. This algorithm is a combination of Centroid as range-free based algorithm, and hop-based connectivity algorithm. Nodes have a possibility to estimate their own position based on the connectivity level between them and their reference nodes. Each node divides its communication range into several regions where each of them has a certain weight depends on the received signal strength. The weighted value is used to obtain the estimated position of nodes. Simulation result shows that the proposed algorithm has up to 3 meter error of estimated position on 100x100 square meter observation area, and up to 3 hop counts for 80 meters' communication range. The proposed algorithm performs an average error positioning up to 10 meters better than Weighted Centroid algorithm.

Keywords: adaptive, connectivity, centroid, range-free.

1. INTRODUCTION

Environment condition has an effect on distance measurement for node positioning in wireless sensor networks and its applications [1], [2]. The presence of obstacle and other signal sources around the observation area will interfere on transmitting signal. This signal also suffers from attenuation, reflection and absorption due to environmental condition. There are two kinds of node positioning schemes: range-based scheme and range-free scheme. Range-based scheme applies Received Signal Strength (RSS) model using RF signal, and Time of Arrival (TOA) model using ultrasound to estimate the distance between source and destination node. Meanwhile, range-free localization offers distance estimation process without any physical measurement. This scheme could be figured out by using the consideration of hops between nodes, the proximity of node, or relative distance between sensor nodes and their references. The information of hops can be attached into the transmitted packet. Once a node receives a packet, the hop will be increased by one. Finally, the destination node receives a number of hops, depends on the far of distance toward the other nodes. In short, range-free scheme offers a lower infrastructure cost compared to range-based scheme.

The lack of range-free localization scheme lies on the emerge of coarse of estimated distance due to approximated hops for distance calculation. Therefore a hard-won effort is required to obtain a sophisticated algorithm to refine the estimated position of sensor nodes.

In this paper, we propose a range-free localization algorithm with connectivity concept to improve the existing centroid node position model. The algorithm is named as Adaptive Connectivity-based Centroid (ACC). Using this scheme, the estimated position of a node is calculated based on the proximity of nodes towards their references. The power level of unknown node is considered as an indicator to determine the selected reference nodes. This is an extension scheme of the previous work which explained about the connectivity-based centroid without consideration of power level [3]. We propose a combination of received signal strength and hop count information, to construct the weighted link between nodes and its neighbors. The hop count information is inserted by the node into the flooding packets when the node is visited by these packets. The combination of RSS and hop based information has been proven to give more accurate result in the estimation process of node position.

The rest of the paper is organized as follows: In section II, we give a background of the lack of centroid scheme and the reason why we must concern about it. In section III, we provide the basic centroid and the proposed algorithm. The experimental analysis and simulation result are discussed in section IV. The conclusion and future works are explained in section V.

2. RELATED WORKS

The centroid method proposed by [4]–[7] was using a weighted factor indicated the connectivity between unknown node and their adjacent nodes. Received signal strength had a proportional relationship with the distance of nodes. The bigger the signal received, the closer the distance was obtained. The weighted factor had been claimed by Blumenthal showed that this factor was inversely with RSS value. The bigger the RSS value - indicated the greater the distance between nodes – the smaller the weighted factor would be provided. Centroid based positioning with involving weighted factor had been proposed by Yun by using edge weights of adjacent reference nodes based on TSK fuzzy modeling. The adjacent reference nodes which were connected to the node had been selected then he developed the fuzzy membership function based on received signal strength (RSS) information between the node and reference nodes to estimate the position of nodes. Both aforementioned proposals rely on the receiving signal strength information to solve the estimated distance.

Meanwhile, another range-free based node positioning method proposed by [3] was using recursive process to estimate unknown node positioning. When the position of certain node had been obtained, it would be used as a reference for the other nodes to calculate their position by centroid algorithm. The procedure was repeated until the estimated position of all unknown nodes had been obtained.

3. ORIGINALITY

Centroid algorithm estimates the position of nodes by averaging the coordinates of its adjacent nodes. In this algorithm, the most optimal results will be given if the position of node is located right in the middle of the adjacent node set. The uniformity of the distance of each adjacent node toward the node itself becomes one the node requirement to optimize the calculation of node position. This means that almost all of the adjacent nodes are located at the same distance with the unknown node, they form a circular or hexagonal topology. Unfortunately, in the real applications, the kind of this topology is impossible to obtained.

Figure 1 shows several possibilities of estimated node position using Centroid algorithm. A few number of references or adjacent nodes and the asymmetrically position of them is depicted in Figure 1a). This situation yields a fairly large error on estimated position, because node receives less information about the reference node's position. If the number of the reference node involves is increased, as shown in Figure 1b), however, the node with more accurate estimated position will be obtained. The other reason of a non-optimized node positioning is caused by the character of node distribution. In uniformly node distribution, the more accurate estimated node positioning will be given. This is inversely with a non-uniform node distributed, as shown at Figure1c). Furthermore, symmetrical and uniform distribution of nodes is the most favorable conditions to increase the accuracy of node estimated position, see Figure 1d). Within this circumstance, the error position could be minimized as well. The black marker on Figure 1 shows an actual position of unknown nodes, whereas the red one indicates the estimated position solved by Centroid algorithm. Based on aforementioned facts, Centroid algorithm still needs to be addressed by implementing some correction factors to acquire an optimal node estimation position.

Weighted Centroid Algorithm proposed by [4] offered an inversely distance as a link weighted of a pair of node. The drawback of this method was due to the implementation of range-based scheme to estimate the distance between the nodes, that need to be provided an enormous cost.

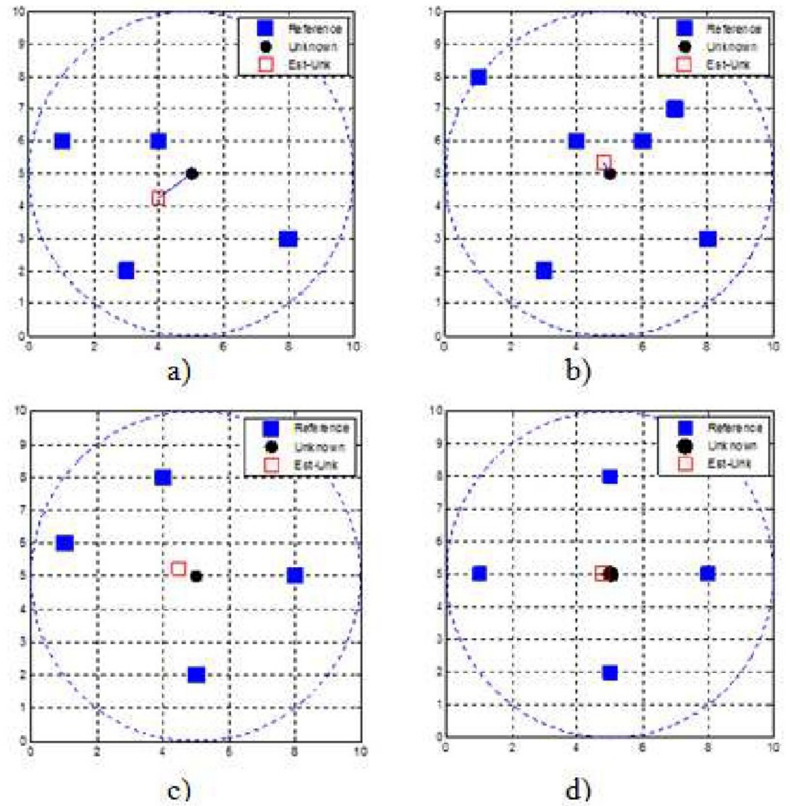

Figure 1. A centroid scheme to solve the estimated position problem for

a) Non uniform distribution with few reference nodes
b) Non uniform distribution with large number of reference nodes
c) Uniform distribution with few reference nodes
d) Symmetric, Uniform with few reference nodes

Based on the drawback of estimated position resulted by centroid algorithm and weighted centroid, we propose zoning mechanism, a procedure to divide node's coverage area into several regions. This mechanism is associated with the capability of zigbee module in adjusting its power level while it is serving the communication process among nodes. The adjustment is adaptive depend on the hop count information between reference node and the node which calculates its position. This is the originality of the proposed algorithm, which is not to be mentioned by the previous works. Using this mechanism, range-based implementation in centroid algorithm would be reduced gradually.

4. SYSTEM DESIGN

The problem formulation of Centroid Algorithm was described as follows: Assume there was 2 dimensional observation area LxL m^2, with $m+n$ nodes deployed on it, where m and n were the amount of reference nodes and unknown nodes, respectively. In this paper, the term of anchor node states a sensor node which had a priory position, which is manually placed. Gateway and access point were belong to anchor node. The number of anchor nodes was less than the unknown nodes. Unknown nodes were randomly deployed due to the prohibited situation of the observation area. This node was estimating its position with the assistance of reference nodes. Reference node was a part of anchor nodes which had the capability to communicate with unknown node. The signal that transmitted by these nodes could be reached by the unknown node. If the coordinate of a node was expressed as *Z* where $Z=(x,y)$, then the anchor nodes had a set of two dimension coordinates as $Z_j=(x_j,y_j),\ j=\{1,2,\dots,M\}$ and the coordinates of unknown nodes were $Z_i=(x_i,y_i),\ i=\{1,2,\dots,N\}$. Reference nodes were part of anchor nodes, which their amount was less than anchor nodes, and the coordinates of them were $Z_k=(x_k,y_k),\ k=\{1,2,3,..,P\}, P\le M$. A reference node *k* had the capability to establish the communication link with unknown node *i* when the requirement of $d_{ik}\le R_k$ was fulfilled.

Sensor nodes – in this case were represented by unknown nodes – were detecting the presence of the other nodes around them by receiving their information. This information contains 2-dimensional coordinates of the reference nodes. All possibilities of coordinates information which transmitted from involved reference nodes were collected by sensor nodes and they would be used for calculating sensor nodes position. The estimated node position was expressed as the Basic Centroid Algorithm as follows [8]:

$$(\hat{x}_i,\hat{y}_i)=\left(\frac{\sum_{k=1}^{P}x_k}{k},\frac{\sum_{k=1}^{P}y_k}{k}\right) \tag{1}$$

With *P* was the number of involved reference nodes where the coverage area of these nodes could be achieved by sensor nodes.

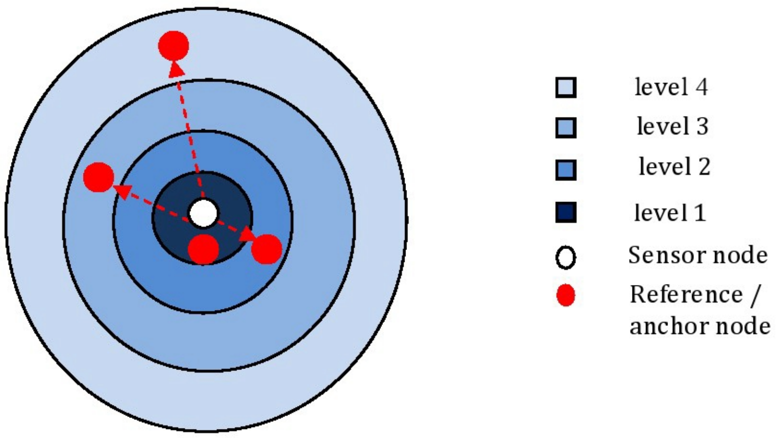

Figure 2. The adjustment of power level on a sensor node

The proposed Adaptive Connectivity-based Centroid (ACC) algorithm refers to the consideration of the sensor node power level, as shown in Figure 2. This power level is used to obtain the symmetrically of the reference nodes involved. Based on the ability of wireless Zigbee as a communication module of the node, the power transmit of node could be adjusted in several levels. The bigger the power level is given the wider the coverage area is obtained. Similarly, the ability of receiving a signal of unknown node by Zigbee module could be adjusted in several levels as well. Generally, in simulation-based research, the communication range for each node has the same value, R_k.

A hop information - called hop-count will be inserted in the sending packet. The sending packet is started moving from a reference node. Each packet contains reference node ID, sensor values, 2-dimensional coordinates of reference node, and a hop count. It stated as $\left\{ID_k, S1_k, S2_k, ...Sn_k, (x_k, y_k), h_k\right\}$. The hop-count has started from zero when it transmitted from a reference node and it incremented by one if the packet visits a node. The counting is repeated until this packet reaches the destination node. Finally, this node will receive the number of hops. The received hop-count is depends on how far or how close the distance of unknown node toward reference nodes. This proposed model seems to be closer to DV-Hop model that has been introduced by [9].

Hop information is presented as a correction factor from the weighted obtained from received signal strength. As proposed by the previous paper [4], a weighted factor from the link between reference node k and sensor node i, w_{ij} is inversely proportional to the received signal strength (RSS). The stronger the signal received, the shorter the distance, D obtained, the bigger the weighted factor, w_{ij} is obtained as well. This statement can be written as:

$$w_{ij} = \frac{1}{D_{ij}} \tag{2}$$

The adjustment of power level relies on the maximum hop, $h^i_{\max}$ which received from each reference node, as shown in Figure 2. The highest level is given to zone I, which is the closest area from sensor nodes. This zone has a biggest connectivity-weighted w_{ik} and a lowest hop order. Meanwhile, the lowest zone is the furthest from the center of node. This zone has a lowest connectivity-weighted, and a highest hop order.

The relationship between weighted factor, hop count and RSS distance is could be expressed as follows: The weighted factor is inversely proportional to two squared order of maximum hop, plus RSS distance, and it stated as:

$$w_{ij} = 1 \Big/ \left(2^{2^{\wedge} h^i_{\max}} + D_{ij}\right) \tag{3}$$

With $h^i_{\max}$ is a maximum hop taken from reference node k toward the sensor node i, and D is an RSS distance from both sides.

Sensor node will initiate the estimated node positioning with maximum hop received from all reference nodes. To be noticed, the reference node is the node which its signal strength could be achieved by the sensor node. The region between sensor node i and the reference node which giving maximum hop, is split into M zones with M= $h^{i}_{\max}$. All nodes in the lowest zone will have the same weighted factor, which expressed as:

$$w_{ik} = 1 \Big/ \left(2^{2^\wedge\left(h^{i}_{\max}-1\right)} + D_{ik} \right) \tag{4}$$

The next closer zone has $h^{i}_{\max} - 2$ order of weighted factor and so on. The closest zone from the node core has a weighted factor which expressed as:

$$w_{ik} = 1 \Big/ \left(2^{0} + D_{ik} \right) \tag{5}$$

The modified form of Eq. (1) yields Eq. (6). This is an expression of estimated node position using weighted factor, w_{ik} which is calculated from (3) to (5). In this form, each coordinate of involved node is multiplied by the weighted factor, and the sum of multiplication is divided by the sum of total weighted.

$$\left(\hat{x}_i, \hat{y}_i\right) = \left(\frac{\sum_{k=1}^{P} w_k x_k}{\sum_{k=1}^{P} w_k}, \frac{\sum_{k=1}^{P} w_k y_k}{\sum_{k=1}^{P} w_k} \right) \tag{6}$$

Both ACC Algorithm and Weighted Centroid Algorithm are using Eq. (6) to calculate the estimated node position. Furthermore, Weighted Centroid Algorithm implements Eq. (3) to calculate a weighted factor in a link between reference and unknown node. Meanwhile, ACC Algorithm applies Eq. (3) to (5) to calculate the same parameter.

The weighting algorithm of Adaptive Connectivity-based Centroid is given at algorithm 1.

Algorithm 1

FOR each sensor node, $U_i, i \in \{1, 2, \ldots, n\}$
FOR all reference node information $Z_k = \left(ID_k, x_k, y_k, h_k\right), k \in \{1, 2, .., p\}$
    Obtain maximum hop $h^{i}_{\max}$
    Divide power level of U_i, P^i into $2^{h^{i}_{\max}}$
    Obtain RSS distance, D_{ik}
    Calcucate weighted factor W_{ik} with the rules:
FOR $h^{i}_{\max}$
IF $\left(D_{ik} \geq (h^{i}_{\max} - k)R / h^{i}_{\max}\right)$ AND $\left(D_{ik} \leq R\right)$
        apply Eq. (3)
ELSE IF $\left(D_{ik} \geq (h^{i}_{\max} - (k+1))R / h^{i}_{\max}\right)$ AND $\left(D_{ij} \geq (h^{i}_{\max} - 1)R / h^{i}_{\max}\right)$
        apply Eq. (4) and so on
ELSE
        $w_{ik} = 0$
END for $h^{i}_{\max}$,Z_k, U_i

5. EXPERIMENT AND ANALYSIS

In our simulation, nodes were deployed into two kinds of topologies: grid topology and random topology. In the first model, reference nodes were divided into several rows and columns within the two-dimensional area. These nodes formed a regular grid topology, whereas unknown nodes were deployed randomly. In the second model, both reference and sensor nodes were deployed in Gaussian random distribution, $N(0,1)$. There were 75 nodes in total, with 25 reference nodes and the rest was unknown nodes. The observation area was devised on 100x100 m^2. The selection of 100 meters length was based on the maximum range of Zigbee wireless communication module attached to the node. The simulation was done by Matlab, using certain simulation parameters as shown in Table 1.

Table 1. Simulation Parameter

Parameter	Size	Unit
Node Amount	75	pcs
Observation area	100x100	m^2
Environment Condition	Outdoor LOS	
Communication range	30 – 100	m
Hop Count	1 - 6	hop
Node distribution	Grid, Random	

The reliability of proposed algorithm would be evaluated using those simulation parameters and it compared to weighted centroid algorithm. As aforementioned, the weighted factor in Weighted Centroid Algorithm was inversely proportional to the g order of RSS distance, written as:

$$w_{ik} = 1/(D_{ik})^g \tag{7}$$

Where g was a degree of believe to ensure the effect of reference nodes on the position determination [4].

The evaluation of system was reviewed in terms of comprehensive aspects that were usually imposed on node positioning scheme, such as communication range, the number of hops and node density in the observation area. Both algorithms, i.e. ACC as a proposed algorithm and Weighted Centroid algorithm as a previous related work, were adequately accurate in grid topology deployment, but not in random topology due to the inequality spreading of nodes. In this situation, obtaining the reference nodes with a symmetrical position indeed became an impossible matter. Figure 3 shows the performance of proposed algorithm and Weighted Centroid algorithm implemented on grid topology nodes. The simulation was running at 100x100 m^2 observation area with 50 unknown nodes, 25 reference nodes, hmax was varied at 2 – 3 hops, and it took 40 m communication range. The g factor for Weighted Centroid algorithm was adjusted at 3.

The reliability of Centroid localization scheme leans on the average error of estimated node position. This error had impacted by communication range of each node and density of reference nodes in the coverage area of sensor node. The wider the communication range was given, the bigger the area was covered, the more the node amount would be involved in positioning process. In the case of the proposed ACC scheme, the number of

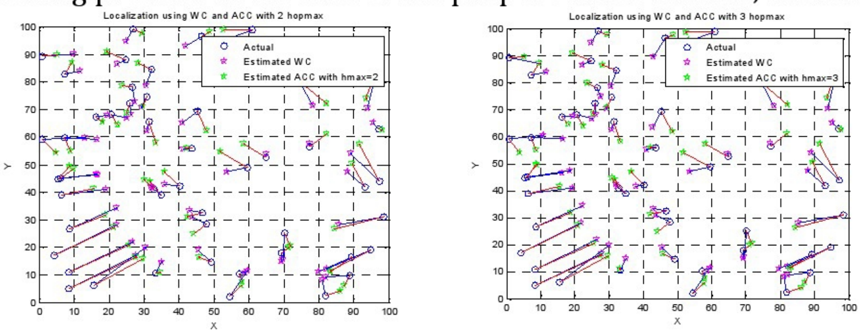

Figure 3. Node positioning with ACC and WC Algorithms in grid topology
Left: WC (g=3), ACC (h_{max}= 2) Right: WC (g=3), ACC (h_{max}= 3)

maximum hop that served to split the coverage area into several zones would affect to the average position error too. The average error position of the system is expressed as a eucledian distance between actual and estimated position of each node divided by the number of the amount of sensor node, which stated as

$$MSE = \frac{1}{n}\left(\sum_{i=1}^{n}\sqrt{\left(x_i-\hat{x}_i\right)^2+\left(y_i-\hat{y}_i\right)^2}\right) \tag{8}$$

We evaluated the effect of of maximum hop count toward Mean Square Error (MSE) of estimated position. In the similar observation area, we deployed 25 reference nodes and 50 sensor nodes. Assume that all nodes had an isotropic direction with 40 meters communication range. The number of maximum hop was adjusted between 1 to 6. The power level of nodes was divided into 2^3 or 8 zones. Each zone had been weighed with maximum value $1\Big/\left(2^{2^3}+D_{ij}\right)$ for the closest zone from center of coverage area, to minimum value $1\Big/\left(2^{2^3-\left(2^3-1\right)}+D_{ij}\right)$ for the farthest zone. The simulation result is depicted in Figure 4. The graphical result shows that ACC algorithm would tend to reduce the average error position, or the accuracy of estimation position become higher if the number of maximum hop between reference node and sensor node was 3 or more. This condition was prevailed both at grid topology or random topology.

The effect of increasing node density toward the mean square error of estimated position has been evaluated as well. In the similar area, we deployed 50 sensor nodes with 60 meter communication range of each. The number of reference nodes were varied from 7 to 25 (12.28 to 33.33 % of the total distributed nodes in the observation area). The graphical result, as depicted in Figure 5 shows that MSE of both algorithms (weighted centroid and the proposed one) tends to decline with the increasing of reference

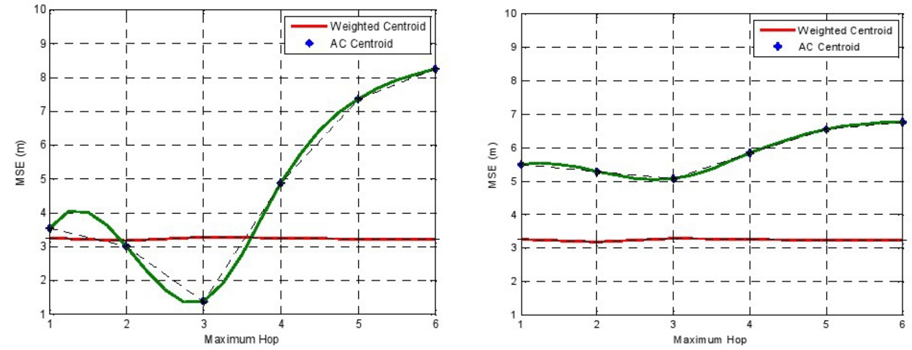

Figure 4. Average error position towards maximum hop number
Left: Grid topology Right: Random topology

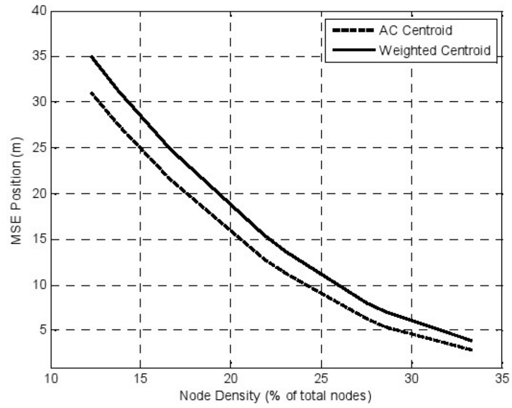

Figure 5. Average error position towards node density in the observation area

node's number. This situation corresponds to the characteristic of centroid mechanism as explained at Figure 1. Within this circumstance, the proposed algorithm had the capability to improve the perfomance of weighted centroid up to 14.32%.

6. CONCLUSION

In this paper we propose a new algorithm – called Adaptive Connectivity-based Centroid. Zoning mechanism of node coverage area is implemented on the new algorithm. The proposed algorithm provides the ability to address the performance of weighted centroid which is offered by the previous researcher. The simulation result shows that the proposed algorithm has increasing the estimated position accuracy up to 14.32% than weighted centroid. The average error position obtained by the new algorithm is recorded less than 3 meters at 100x100 square meters of observation area, with 3 or 4 best maximum hop counts. The optimal communication range is attained at 80 meters. In the future, the adaptive zoning mechanism or adaptive power control should be attached to the node to select the best involved nodes for positioning process. This selection mechanism must be taken into account for energy savings.

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