Real-Time Vehicle Location with Desired Accuracy

Soheila V. Bana, Pravin Varaiya

Abstract— **Magnetic markers are provisioned on automated highway system for lateral control of vehicles within a lane. We propose a pseudo-noise (PN) code to be carried by the magnetic markers. The PN code will be used by vehicles for range measurement. Every vehicle is provided with the code layout on the road with respect to the physical location of every binary magnetic signal. A vehicle has a replica of the signal and measures the phase of the received signal with respect to the replica and infers its position on the road. The positioning accuracy is subject to design and depends on the magnetic markers layout on the road. The probability of error with short range magnetic signals is negligible compared with radio navigation systems. Unlike radio signals, magnetic codes do not interfere, and multi-path is not an issue. However, errors do exist and an attractive feature of the method is its error detection capability. Errors can be detected and corrected shortly after they occur and the error detection and correction delays are subject to design. Error bounds can also be specified with respect to the signal code design.**

Keywords— **Vehicle Location, Positioning System, Navigation**

I. Introduction

VHICLE location is a necessity for vehicle control and communication in automated highway systems (AHS) [1], [3], [2], [4]. Current positioning systems use radio signals which can achieve relatively high accuracy under specific circumstances. However, systems that use radio signals may have problems with interference, fading, and multipath. We use the mathematical approach of the Global Positioning System (GPS) to range measurement but we propose a different implementation strategy. GPS uses pseudo-noise (PN) signals for range measurement [5], [6], [7], [8], [9], [10], [11], [12]. PN signals provide excellent accuracy in range measurement due to their correlation and autocorrelation properties. However, GPS may not be the right solution for vehicle location in AHS because of the multi-path problem [13], [5]. Accuracy in positioning is important for AHS and an automated vehicle at any point must be aware of its degree of location accuracy in position location to choose its control policy accordingly. Vehicle-to-vehicle communication could also rely on accurate positioning [4].

We propose a novel method for vehicle location in AHS that employs magnetic signals to transmit PN codes. AHS design relies on magnetic markers for lateral control of vehicles within a lane [14]. A vehicle has a magnetometer to follow a sequence of markers centered on the lane. We propose a technology for vehicle location that takes advantage of this AHS infrastructure.

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The magnetic markers are binary coded using their dual polarity. The sequence of the binary magnetic markers at each lane is coded to yield a pseudo-noise signal that is unique to that lane in the AHS network. The phase of the pseudo-noise signal represents the receiver's range from the beginning of the sequence on the lane. A vehicle resolves its absolute position on the road by estimating the signal phase. The signal properties insure accurate phase estimation. The advantage of the method over other navigation technologies is that it provides continuous accurate positioning with the desired level of accuracy. Moreover, vehicle positioning is obtained in real-time with little data processing. Radio navigation technologies fail to promise continuous accuracy due to signal fading and multi-path problems.

II. Background

There are some required specifications for vehicle location that must be considered for system feasibility within AHS. In the following, we review the major design specifications for vehicle location in AHS.

A vehicle location system in AHS must maintain its integrity independent of other components of the AHS system. Similarly, functionality, precision, and accuracy of the system must be independent of the physical environment, weather condition, surrounding walls (tunnels), and road visibility. Moreover, it must maintain a certain level of precision and accuracy. Increased precision allows for reduced space taken by vehicle maneuvers. Thus, throughput of the automated road is improved as the positioning system becomes more accurate. Furthermore, the system should allow an estimate of the positioning error in order to detect faults. This allows vehicles to avoid or abort unsafe maneuvers. It is desired that the positioning errors be bounded and the error bounds be known to the system designers. Given an AHS design, the system level requirements of the design will impose constraints on a feasible positioning system and its error bounds that can be tolerated. Finally, the system economy must be considered. Feasibility of the positioning system well depends on its cost.

The proposed system meets the AHS requirements and the system is economically feasible because it takes advantage of the infrastructure and characteristics of the automated roads. These characteristics are not met by the current radio navigation systems including GPS.

In Sections III and IV we present maximal length PN sequences and their properties and explain how they are used for real-time vehicle location. In Section V we indicate the effects of the selected code length on system performance and in Section VI we present an error analysis of the proposed positioning system. Finally, in Section VII we briefly compare the proposed system and GPS and provide some suggestion for system improvement.

III. Maximal Length PN Codes

PN codes are excellent for range measurement and are used by GPS. The length, type, and bit rate of the selected PN code determines the capabilities of the ranging system. The maximal sequence codes are the longest codes that can be generated by a given set of shift registers. The bits of PN sequences are called *chips* to underscore that these codes do not carry data. The feedback configuration determines the length and type of the sequence. Given n binary shift register sequence generators, the maximum length sequence has $2^n - 1$ chips. Even though the sequences have some randomness properties, the maximal linear sequences are deterministic as sequences repeat at intervals of $2^n - 1$ chips. Each repetition exhibits the same one-zero distribution. The statistical distribution of ones and zeros is well defined and always the same. As the window of observed values within a period increases, the randomness of one-zero distribution decreases. In the following, we review some important properties of the maximal length PN codes that contribute to the error detection and correction capabilities of the proposed positioning system [5], [15].

A. Predictable Sequence

Knowing n, the number of shift registers, and $2n$ consecutive chips of the code, one can predict the entire length of $2^n - 1$-chip code. This is because the feedback configuration can be realized by solving equations of the form $b_i = \sum a_j b_{i-j}$. Since there are n stages and each could be involved in the feedback configuration, n equations are needed.

$b_{n+1} = a_1 b_n + a_2 b_{n-1} + \ldots + a_n b_1$
$b_{n+2} = a_1 b_{n+1} + a_2 b_n + \ldots + a_n b_2$
$\ldots$
$b_{n+n} = a_1 b_{n+(n+1)} a_2 b_{n+(n-2)} + \ldots + a_n b_n$

The equations have overlapping blocks of $n+1$ consecutive chips from the sequence, and n equations are needed, which sets the required number of known chips to $2n$. Thus, the feedback structure of an n-stage shift register can uniquely be determined from $2n$ chips. For example, having 20 chips of a 10-stage shift register, one could predict the entire $210 - 1 = 1023$ spectrum communication, is used to great advantage in the system.

B. Large Index of Discrimination

Index of discrimination (ID) denotes the difference in correlation between a fully correlated, i.e., perfectly synchronized, code and the peak of minor autocorrelation or of cross-correlations as depicted in Figure 1. Maximal sequence codes have a large ID which makes them suitable for positioning systems. Autocorrelation of a maximal code is such that for all values of phase shift the correlation value is -1, except for the ± 1 chip phase-shift, in which correlation varies linearly from -1 value to a maximum $2^n - 1$. The autocorrelation function $R(\tau) = \sum_{i=1}^{n} b_i b_{i+\tau}$ is depicted in Figure 2 where $b_i b_{i+\tau}$ is equal to 1 if $b_i = b_{i+\tau}$, and -1 if $b_i \neq b_{i+\tau}$. The plot shows the number of agreements minus disagreements over the length of the two codes being compared, as the codes assume every shift number in the set of shifts of interest. Such a plot is two-valued, with a peak only at the zero shift point. This is an invaluable property because it allows the receiver to discriminate between signals on a yes-no basis.

When the period $2^n - 1$ is large, the full period correlation loses some of its value as a design parameter. Correlation calculations in this case typically are carried over blocks of K chips, where K is larger than n, the number of stages of the code generator, and smaller than the code period, $2^n - 1$. A more appropriate statistic for study in this case is the partial autocorrelation defined as $R(\tau, K) = \sum_{i=1}^{K} b_i b_{i+\tau}$. This computes the cross-correlation between two blocks of K symbols, one block located symbols from the other.

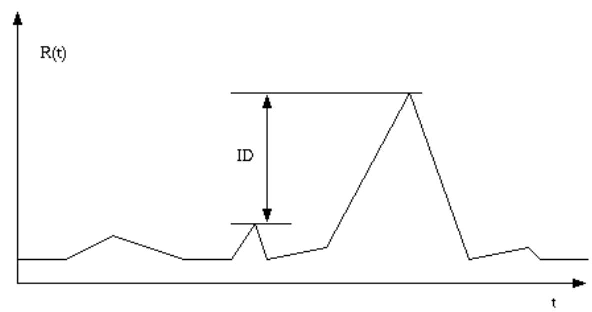

Fig. 1. *Index of discrimination (ID)*

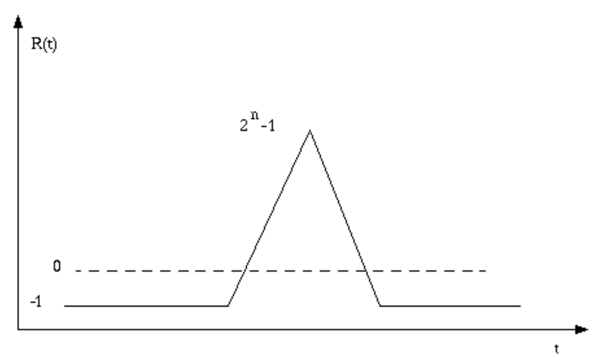

Fig. 2. *Autocorrelation function of maximal length PN codes*

C. Balanced Zero-One Statistics

The number of ones and zeros are equal in a sequence. For example, a 127-chip code has 64 ones and 63 zeros. The number of ones in any linear maximal code is $2^n/2 = 2^{n-1}$, and the number of zeros is $2^n/2 - 1 = 2^{n-1} - 1$, where n is the number of stages in the code generator, and the code length is $2^n - 1$ chips. This randomness property allows for a low value of autocorrelation of a PN code with its phase-shifted replica. This property is used in phase measurement.

D. Exact Number of Runs

A run is a finite sequence of repeating ones or zeros. Relative positions of the runs vary from code sequence to code sequence, but the number of each run length does not. Freymodsson has shown that there are exactly $2^{n-(m+2)}$ runs of either ones or zeros of length m in every maximal code sequence [15]. The exception is that there is only one run containing n ones and one containing $n-1$ zeros. There are no runs of zeros of length n or of ones of length $n-1$.

E. Phase-Shifted Replica Addition

A modulo-2 addition of a maximal linear code with a phase-shifted replica of itself results in another replica with a phase shift different from either of the originals.

IV. Real-Time Vehicle Location

We use the properties of maximal sequence codes in positioning by magnetic markers. The process of position location is illustrated in Figure 3.

Assume that the magnetic markers in each lane are coded with a unique maximal code with a linear span of n. By *Predictable Sequence* property, reading a $2n$-chip segment of a maximal code is sufficient to predict the entire period. The vehicle can figure out the feedback configuration of the code, and build the related feedback configuration and generate a replica of the code.

Large Index of Discrimination allows perfect synchronization of the vehicle replica and the received signal. This enables the vehicle to estimate the exact phase of the magnetic PN code and figure out its absolute position using the location map of the code layout.

Exact Number of Runs guarantees that a $2n$-chip block uniquely determines the code phase. The proof is by contradiction. Suppose a $2n$-chip block is repeated within one period. Shift a replica of the code, and add it to itself such that the two similar blocks add. By *Phase-Shifted Replica Addition*, this would result in another replica with a phase shift different from either of the originals. This would result in a $2n$-long run of zeros while the maximum run length for zeros is $n-1$ by *Balanced Zero-One Statistics*.

After synchronization, position updating is done by tracking the magnetic signal and checking it against the replica. Tracking is done by predictable partial autocorrelation. The code is predictable by the receiver, and it is partially being autocorrelated with its replica, i.e., over a partial period of $2n$ chips. As long as the autocorrelation function results in the maximum value, which is equal to the number of received chips, the reading is assumed to be correct.

Tracking allows the vehicle to detect the errors in reading the magnetic code. For example, assume the next chip in the replica is "1", but the next reading of the received signal is a "0", or vice versa. In this case an error is detected, and the receiver must read a sufficient number of chips correctly before it can assert a re-synchronization. Note that no false errors are detected. However, error detection may not happen in real time. For example, assume that the first "1" in a run of five "1"s is missed by the receiver. The missed "1" is shown by "$\emptyset$" below.

$received-code$ $\ldots 0\emptyset111100\ldots$

$replica-code$ $\ldots 01111100\ldots$

The receiver will not know the missed reading until it reaches the end of the run in the received signal, and starts receiving zeros. The error in positioning is only one magnetic spacing (chip), but it takes a five magnetic spacing trip for the receiver to detect the error.

Figure 3 shows that in case of an error, $2n$ chips must be read for re-synchronization. The optimum number of chips depends on the specific code and could be smaller than $2n$.

Currently, the markers are designed to provide specific information such as road curvature [14]. A mapping that provides information about the absolute position of a vehicle on the road can be linked to other data about the road, travel information, etc.

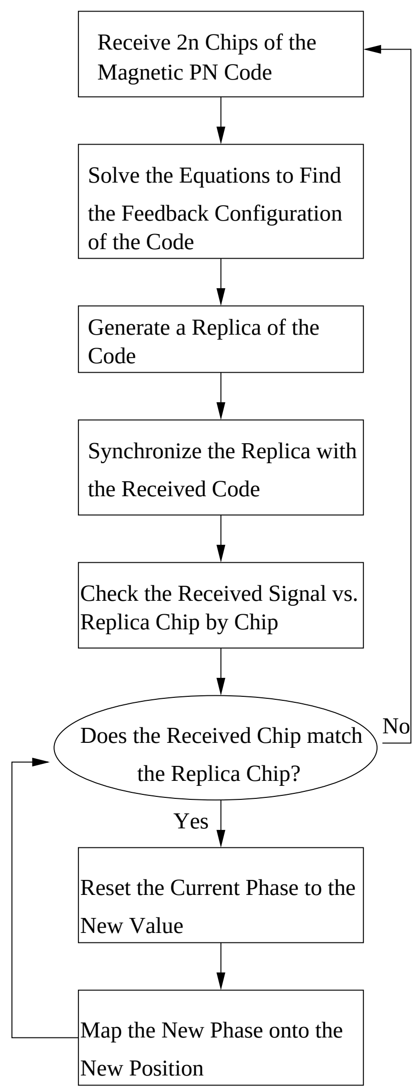

Fig. 3. *Flow diagram for magnetic positioning system*

V. Code Selection

Consider the set of magnetic sequences $\mathcal{S}$ that are used for positioning by magnetic markers, and the set of road maps $\mathcal{L}$. There must be a one-to-one mapping $\theta : \mathcal{S} \rightarrow \mathcal{L}$ unique physical representation . Suppose there are N automated roads in an area, and each has M automated lanes in both directions. This makes a total of $N \times M$ magnetic codes and requires the same number of physical interpretations. Thus, a vehicle that knows the phase of the magnetic signal can obtain its position on the road.

A design issue in phase synchronization is that the code must be long enough to avoid any ambiguity in resolving the phase of the code, i.e., the period of the magnetic sequence must be longer than the road. After synchronization, the position update during the motion must be tracked by predictable partial autocorrelation. Synchronization is possible by reading $2n$ chips where we can choose a set of codes of equal length of $2^n - 1$. Assume that the distance between two consecutive magnetic markers is one meter. A vehicle must travel $2n$ meters before it can initialize its position and start updating it by tracking the signal. If the linear span of the code, n, is too large, it will take a long ($2n$-chip) travel distance and computation time for a vehicle to find its location. If the code period is so short that the code period is shorter than the road length, it could cause ambiguity about the number of code periods that are repeated on the road. When a vehicle enters the road, or changes lane, it must be able to initialize its position without ambiguity.

Another consideration for code length is the number of different codes that we would like to have for synchronization. The maximum number of different codes of length $2^n - 1$ is limited by $(pf_1 - 1)(pf_2 - 1)\ldots/2n$, where pf_1, pf_2 ,... are the prime factors of $2^n - 1$ [15].

Let us consider an example case where we choose $n = 21$. The prime factors of $2^{21} - 1 = 2,097,151$ are 7, 7, 127, and 337. There are unique codes of the length $2^{21} - 1 = 2,097,151$ meters, which is well beyond the length of the road. The feedback configuration of the road can be computed from $2n$ chips, and hence, the entire code can be predicted. A vehicle has to travel $2n$ chips, or 42 meters, before identifying the code.

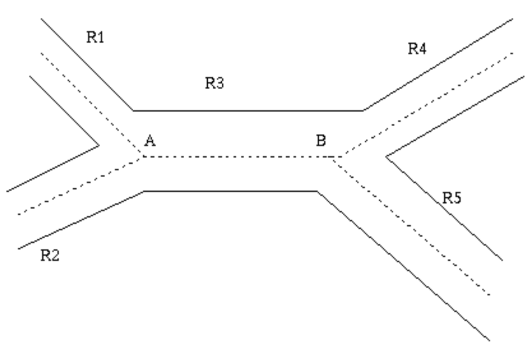

Fig. 4. *A branching road requires special considerations in PN code design.*

In case of branching roads, such as in Figure 4, each road could have its own code, or the consecutive segments $R1$, $R3$, and $R4$ could have one code, and $R2$ and $R5$ have two other different codes. Assume a vehicle is moving from $R2$ to $R3$ where the code sequence changes at point A. If the receiver is not aware of the code change, it will detect errors in partial autocorrelation and will try to re-synchronize with the code of $R2$, whereas it really needs to identify code $R3$ and synchronize with it. In this case, the coding at point A must be such that the starting code of $R3$ has a low partial correlation with the replica of $R2$. Hence, the receiver detects an error as soon as it starts reading $R3$ code, and will identify the new code and perform synchronization. Alternatively, the software could provide road information such that a vehicle that is going from $R2$ to $R3$ is aware of the road change and knows the new code and will only perform a synchronization upon entering $R3$.

VI. Error Analysis

It is important for vehicles to choose their control policy based on the information accuracy. In case accurate information is not available, vehicles should be aware of the degree of available accuracy and perform accordingly. For example, if the safety space gap around a vehicle for lane change maneuver is set at 30 meters, and a vehicle's degree of accuracy is ± 1 meter, it must keep a distance of 31 meters to count for a possible error.

The error analysis of positioning with magnetic markers is conditioned on the fact that the lateral control of vehicle is working properly. This implies that the error cannot exceed certain amount specified by lateral control regulation. The magnetic markers are the essence of lateral control and the error probability p is very small, currently its specification is in the order of 10^{-3}.

The error in positioning by a magnetic signal is due to error in the signal. The error could be received due to (i) missing a marker, (ii) misreading a marker (reading a "0" as a "1" or vice versa), or (iii) reading magnetic noise that is not a marker and was not meant to be read.

A. Missing a Marker

There are exactly $2n - (r + 2)$ runs of length r for both "1"s and "0"s in every maximal code sequence except that there is only one run containing n ones and one containing $n - 1$ zeros [15]. There are no runs of zeros of length n or ones of length $n - 1$. We consider cases of (a) missing one marker, and (b) missing two or more markers where we assume that the distance between two consecutive markers is one meter.

We first consider case (a). An error that happens during a run length will be detected at the beginning of the next run. If the last chip of a run is missing, reading the first chip of the next run will immediately reveal that there is a missing chip, i.e., an error has occurred. Otherwise, the error would drift and a vehicle will not notice the miss until it starts reading the next run. There are a total of $2^n/2^1$ chips at the end of a run, $2^n/2^2$ chips next to the end of a run,...., and $2^n/2^m$ chips are in the position of $m - 1$ chips before the last chip in a run. Assume uniform probability of missing a chip in a code period. Then, with probability of $1/2$ when a chip is missing, the error will be carried for one meter travel, with probability of $1/2^2$ the error will be carried for two meters, and with probability of $1/2^{2m}$, the error will be carried for m meters. The expected number of meters that a one meter error is carried before the error is detected is 2 meters, $1\times 1/2+2\times 1/2^2+\ldots+n\times 1/2^n \leq 2$. The worst case of error drift is when a vehicle travels n meters before it detects an error of one meter it has been carrying in its position because by *Exact Number of Runs*, the maximum run length is n chips.

We now consider case (b) of missing two or more markers. Similar to case (a), the expected number of meters that a car travels before an error is detected can be calculated. However, in this case we need to know the exact code to estimate the number of magnets a vehicle reads before it detects an error.

B. Misreading a Marker

This will immediately result in error detection as the partial autocorrelation function will be reduced from the expected maximum value. A vehicle then can re-synchronize its receiver, and update its position. The probability of misreading a marker can be significantly reduced by improved software algorithms or implementing hardware.

C. Magnetic Noise

This is due to presence of a magnetic field, i.e., a magnetic object on the road. Since magnetic field is inversely proportional to the third power of distance, the source of magnetic noise must be physically very close to the markers on the road. It is likely that such sources of noise are detected and removed before the road is utilized. However, we must count for the low probability of confronting such noise. When noise is introduced, assume that lateral control remains in place and vehicle continues to read the magnetic markers. Furthermore, assume that a noise has equal probability of being a zero or one. If the polarity of the noise chip matches the polarity of the current run, it will not be detected until the end of the run. This is similar to error detection in case (a). If a noise with opposite polarity of the current run happens, it will be immediately detected, similar to the case (ii).

D. Error Detection and Correction

Assuming one meter distance between markers, and the error probability p in reading markers, the amount of error is one meter with probability of p. Assume uniform distribution of error type (i) over a code period. Errors will not be drifted and accumulated beyond one run. Predictable partial autocorrelation is used in obtaining the phase of the code, and respectively, the position of the vehicle. Perfect partial autocorrelation can be achieved when the received signal and the synchronized replica match, i.e., $R(K,\tau)=K$ where $K<2n$ is the number of received chips that the receiver can hold in the buffer. If a vehicle holds K received chips in its buffer, but $R(K,\tau)<K$, then an error has happened. However, an error may not be detected instantly. As an example, consider the following portion of a code

...011111000....

The vehicle is reading the run of ones and is checking the received chips against its own replica of the signal, i.e., is calculating the partial autocorrelation function. As long as $R(K,\tau)=K$, where K is the number of received chips in the buffer, it will not detect an error. Suppose the first “1” of the run is missing, and the vehicle starts reading the run with the second “1”. The missed marker is shown by “$\emptyset$” below.

...0$\emptyset$1111000....

The vehicle will not detect the missed chip until it reaches the end of the run, i.e., starts reading the run of “0”s when it realizes that the autocorrelation is not maximized. The error is detected at this point, and will be corrected by re-synchronization. Thus, an error that happens within one run, will be detected and corrected at the next run. Consequently, probability of having an error of two meters is the probability of two errors occurring within a run which is $\binom{n}{2} p^2(1-p)^{n-2}$ because the maximum run length is n.

The errors do not accumulate, and the beginning of each run confirms lack or existence of error in the previous run. In other words, an error could be carried only during one run without being detected. This may be another consideration in choosing n, the linear span of the code, since the maximum run length within a period is equal to n. Furthermore, during each run, a vehicle can have a maximum of $h-j$ chip errors, where h is the length of the run, and j is the number of received chips in the run. Recall that a quarter of chips in one period of the code have a run length of 1, which improves the accuracy of the system.

VII. Conclusion

We propose magnetic markers in every lane of the road network to carry a pseudo-noise signal similar to the GPS signal. Reading the magnetic signal would allow accurate positioning of a vehicle in real-time. The advantage of positioning by magnetic markers is that it is more reliable than any currently available positioning system and its error bounds are subject to design. While the code structure and range measurement technique is very similar to GPS, the accuracy of this technique is remarkable. A useful feature of the proposed scheme is its error detection and correction capabilities. In the following, we compare positioning by PN coded magnetic markers with GPS.

Both GPS and magnetic positioning systems use PN codes with excellent correlation and autocorrelation properties. GPS uses digital radio waves, and magnetic positioning system uses magnetic pulses. The technology of receiving PN codes, detecting the phase, and mapping it to a physical position is very similar in both receivers. A GPS receiver integrates the entire hardware and software technology, but it depends on differential stations for high accuracy. The components of the magnetic positioning system, the magnetometer and the software, may not be physically integrated, but make an independent system.

Error probability distribution can be tabulated for magnetic positioning while the main source of error for GPS, multi-path, cannot be characterized. Unlike GPS, magnetic positioning system has the ability to detect errors and correct them. The accuracy of positioning by magnetic PN codes is subject to design and can be better controlled than the accuracy of GPS. Moreover, the positioning accuracy could vary over the road by varying the magnetic spacing.

The system can further be improved by augmentation. Inertial navigation system (INS) can be used in conjunction with magnetic PN signal to minimize possible errors [16], [17]. Since INS is relatively accurate in measuring displacement over short distances, it can be used to periodically check the accuracy of positioning by magnetic signal. It is specially useful in checking the accuracy within each run. The error of INS can be zeroed once the vehicle is sure that it is accurately reading the code. Every time a run of "0" or "1" ends, a receiver can assert that its reading at the end of the last run has been accurate. Combining the magnetic positioning system with INS will result in a very high accuracy positioning system.

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