Magnetic Adhesion in Wall Climbing Robots using varied Electromagnet Arrangements

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***Abstract*— The improvements and innovations in the field of robotics have given a great opportunity to perform tasks that are hazardous for humans to perform. For example, robots can be used for working on high-storied buildings, inspection on ferromagnetic surfaces, painting and maintenance of buildings, surveillance purposes, etc., at the outset, to carry out any operation on vertical surfaces, which may be quite hazardous and time-consuming as well, wall climbing robots (WCRs) can be deployed. The method of adhesion determines the stability of the robot on the wall, be it smooth or coarse. Using magnets to bring about magnetic adhesion would be advantageous when the robot is maneuvered over iron or steel surfaces, typically, to clean boilers, etc., This paper presents the different ways of placements of the magnets, both permanent and electromagnets, in order to introduce adequate magnetic adhesion that would cease the robot from toppling down while encountering an obstacle. This work proposes two methods of arrangement of magnets: square and diamond. Four electromagnets when arranged in array formation with 5000 windings of thin copper coil, generated a magnetic field force of approximately 150 N when 50 A of current is passed. By and large, around 35 N to 40 N is the suction force that would be sufficient to stick the WCR of 2kg on the wall, while using a suction chamber instead of electromagnets. Other methods of placing the magnets such as square and diamond are studied and compared as well using FEMM. Hence arranging the 4 electromagnets in array formation gives an adhesion pressure sufficient to hold and move the WCR, over the vertical wall against gravity.**

Keywords*— *Wall climbing robot; Electromagnetic adhesion; Electromagnets arrangements; Magnetic flux linkage.

I. INTRODUCTION

WCRs have been of immense utility to solve real world problems that might bring impairment or loss of human lives. For example, crucial Inspection of large boiler for cracks, gaps, corrosion; repairs in air-crafts, missiles, cleaning and painting of multi-storied building. The WCR must work with ease irrespective of the surface, be it rough or smooth, metal or non-metal etc. [1-3]. The robot is supposed to apply the correct amount of adhesive force towards the wall, in order to maintain stability and be maneuvered effectively over the surface. There are many adhesion methods, popular ones being adhesion due to suction, pneumatic adhesion etc. When it comes to metal surfaces such as steel or iron, magnetic adhesion is used since the surfaces might be smooth and traction is less. Hence for applications of WCR such as boiler cleaning, climbing metal wall for surveillance etc., magnetic adhesion is inevitable [4].

Various adhesion and locomotion principles have been used to build numerous robotic climbers, which can be classified as a) vacuum suction tubes [5, 6], b) pneumatic, c) grasping grippers [40], and d) magnetic adhesion [4-12].

Due to the large number of mam-made ferromagnetic structures that require constant maintenance, the last type of robot has numerous industrial applications that clearly illustrate the urgency in today's society. Magnets of two types [1, 5] can achieve this type of adhesion: a) permanent magnets, and b) electromagnets. Several robot wall climbers based on magnetic adhesion have appeared, namely, a) magnetic tracks [6-22, 35, 36, 45], b) magnetic wheels [6-19, 35, 37, 43, 46], c) soft magnetic muscles [23-26], d) magnetic gripping [27, 46, 47, 49, 54], e) magnetic adhesion pads [34, 51].

Other magnet arrangements of ring and block Neodymium magnets [28], as well as their effectiveness, are investigated, and the process is continued with the optimization of the distance between magnets and the magnetic wall [29, 30]. Some studies [31] deal with the classification of WCR types and how they might be used to make better applications. WCRs are cautious of curvatures and gaps, so identification and detection play a key role in making WCRs work effectively [32], and all of this is listed and discussed [33], as well as the evolution of crawling and climbing robots like gecko, inch worm, and others that take inspiration from biological systems [38, 47, 48, 50, 54], and Pipeline climbing robots [42, 55] use worm-like locomotion to provide high locomotion and help the robot stick to the wall [39], magnetic adhesion will be the strongest force attraction even in water, and Omni-directional robots use advanced propeller mechanisms to provide high locomotion and help the robot stick to the wall [39]. The use of both types of magnets in combination is likewise regarded as an innovative technique [44]. Because pads quickly capture grip of any sort of uneven surface, even electro adhesion for soft substances with an arbitrary time-dependent applied voltage based on surface type [51] is possible.

A WCR must meet a number of contradictory requirements: it must be light to reduce the risk of damaging or deforming the working environment, but it must also have a large payload carrying capacity to carry the necessary equipment. However, it must be able to provide the optimal adhesive force to ensure quick movements without slipping. As demonstrated by the preceding examples, magnetic adhesion is mostly based on permanent magnets (mainly neodymium magnets). The use of permanent magnets improves the reliability of the robot; however, the permanent magnet's high density (7-8 g/cm^3) [4] makes meeting the light weight requirement difficult, whereas electromagnets can overcome the disadvantage of using permanent magnets because they are dependent on an external source, the higher the power, the greater the strength, allowing it to handle large weights with the same number of permanent magnets used for the WCR.

Furthermore, efficient adhesion is determined by the arrangement of the magnets and type of magnets used, permanent or electromagnets. This paper proposes the types of arrangements of electromagnets to achieve sufficient magnetic adhesion. We created novel electromagnet configurations in order to find the best possible arrangement that provides the highest and most changeable magnetic flux in terms of the strength factor required by the surface. The key benefit it offers is the changing magnetic strength necessary dependent on the varied surfaces it travels on [26, 29, 32, 41]. Comparison among the arrangements have also been done to arrive at the best arrangement.

The paper is constructed as follows; Section II comprises of different types of Magnetic mechanisms. Section III describes the ways of arrangements such as square, diamond and array, and finally section IV present out the conclusions with comparisons between different adhesive wall climbing robot's approaches.

II. TYPES OF MAGNETIC ADHESIONS

The mechanism of magnetic adhesion relies upon the type of magnetism used: permanent magnet or electromagnets. Permanent magnets are ferromagnetic materials that are rich in magnetite [5]. When magnetized, they create their own magnetic fields for a longer period of time. They can efficiently hold the WCR adhered to the wall and with varying shapes of the magnets, necessary magnetism is obtained. Variation in magnetic flux can be brought by switching the magnets or by varying the distance between the surface and the magnet. Neodymium Iron Boron Magnet (NdFeB), Alnico, ferrites etc., are best examples of permanent magnets used for magnetic adhesion in WCRs.

Magnetic force can be described by the normal force formula as

$$F = m \times a$$

Where, F is the total magnetic force, m is the mass of the object and a is acceleration. But force also depends upon the strength of the magnet which in turn depends on the size, shape, arrangements of magnets, quality, permeability etc. A general pull-up graph can provide the magnetic strength the magnet can provide over varying distances from the magnetic material like iron or steel surfaces.

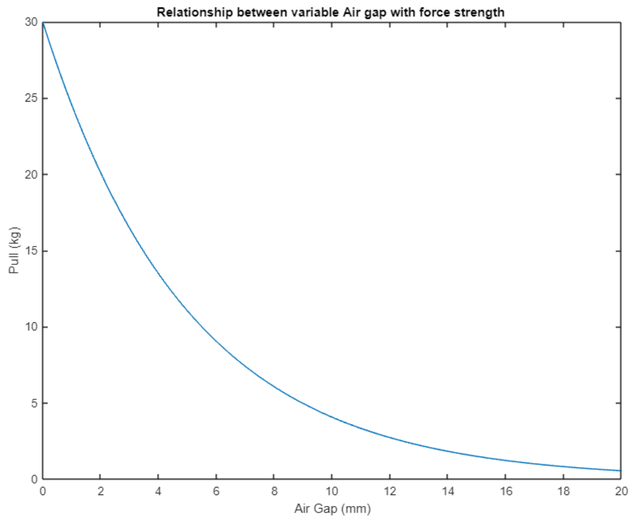

Fig. 1. Air Gap vs Pull

When the WCR moves over steel surfaces, there will definitely be a gap between the magnets placed and the metal surface. It can be noted that when the distance becomes more than 7.5 mm, the there is a fair chance that the WCR might topple down without magnetic adhesion. Care must be taken in order to maintain the air gap below 5.5 mm to aid in continuous motion of the WCR. This is for a single magnet of nominal size. Arranging more magnets together would provide a different graph indicating more strength and resistance from toppling.

On the other hand, electromagnets can be powered up by supplying current through the coil that is worn around the former. The strength of the magnetic field is directly proportional to the electric current supply to coil. The direction of the magnetic field is calculated using Right Hand Thumb rule. Whenever the current is passed though coil, the atoms are charged and arrange/align themselves in, where the current entering point become magnet South Pole and electric current exit point become the North Pole, the change in polarity can reverse the magnetic property and vice-versa.

Principally, the parameters selected for magnetic adhesion for WCR are namely: electromagnetic force, arrangement of magnets, distance between the magnets, distance between the magnets and the metal surface. These parameters are on the basis of the expectation that the WCR does not topple and has good adhesion towards the metal surface. In this work, a WCR which weigh 2 kg is supposed to be pulled and adhered to the wall. Using permanent magnets will be disadvantageous since there is no control over the magnetic field created and generalization of the field for varying weights cannot be done. Moreover, automation of the WCR will also be restricted since it has to be pulled from the wall once its operation is over. Hence, the case of electro magnets and their arrangements to obtain maximum magnetic flux is studied in this work. Permanent magnets having an equal number of adhesive forces in all sides, but the arrangements change the adhesive strength. Two or more magnets are arranged in such manner to change the magnetic field concentration, and thus achieve greater magnetic strength.

III. ARRANGEMENTS OF ELECTROMAGNETS: SQUARE, DIAMOND AND ARRAY

The proposed method is carried out using FEMM software, which contains a model development and analysis section that analyses the model's magnetic field in open space. Fig. 2 depicts the sample model that can be studied.

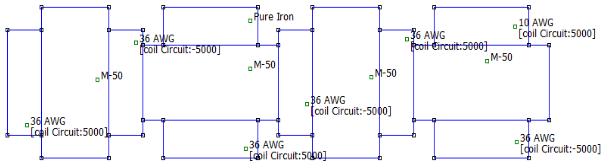

Fig. 2. Array formation of magnets

The flowchart in Fig. 3 provides a quick summary of the flow of the suggested method. Initially, we created a model and defined the problem as electromagnets, then we drew the structure of coils similar to Fig. 1, then we placed the block labels to define the region as metal block or coil which is around the metal block to act as electromagnet, by adding the material to the blocks as M-50 as ferromagnetic substance and 36 AWG with 5000Amp capacity as coil, and finally we created a boundary around the created object to define the space around it as air, water etc. Then, a mesh was built around all boundaries to define each region of space to be covered by the electromagnetic field to generate flux in the region, and FEA (Finite Element Analysis) was run to extract a variety of information from the solution. Finally, the result is plotted into a flux density plot with a table to determine the strength in various regions of interest.

Whenever the current flows in the coil bounded to the soft iron metal, it produces an external magnetic field which induces magnetic property that makes the WCR adhere to the wall. If I is the current passed through coil of length l and n number of turns.

The magnetic field strength or flux H (units A/m) by,

$$H = \frac{nI}{l} \tag{1}$$

In this study, permeability of air is taken as constant for the (1) since the operation of WCR is in the air medium.

In Electromagnetic adhesion, the electric current passed to the coil is directly proportional to the Magnetic field,

$$B = \mu H \tag{2}$$

$$B = \mu\left(\frac{nI}{l}\right) \tag{3}$$

$$\text{Thus, } B \propto I\,, B \propto \frac{1}{l} \text{ and } B \propto n \tag{4}$$

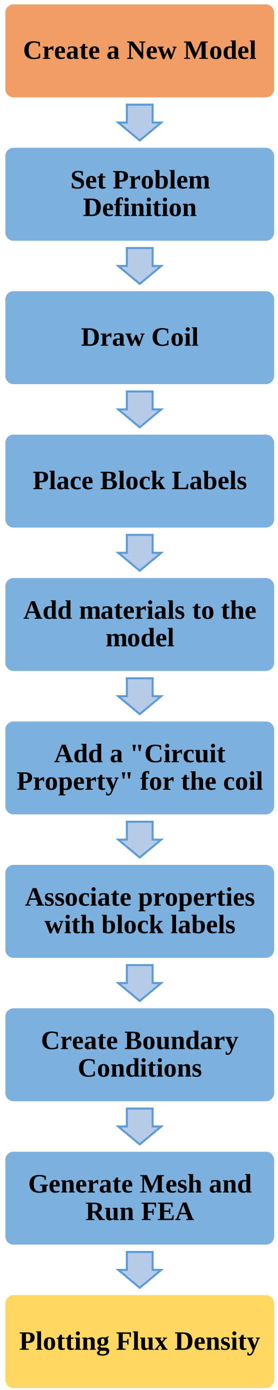

Fig. 3. Flow chart

The entire work is modelled in 2D framework space and numerically identified using FEMM (Finite Element Method Magnetics) software, which use the Finite Element Method analysis (FEA) to calculate the magnetic field generated by each configuration of electromagnet. The following arrangements were investigated: a) Square arrangements, b) Diamond arrangement, and c) The Halbach array. The various configurations and associated flux density diagrams are recorded separately (arrows on each magnet indicate the north pole of the magnet).

Fig. 4 shows the increase in magnetic flux with increase in current I and number of windings n referenced via (4). For 50 A and 20 windings, the magnetic flux achieved is >=1000

Tesla. According to (4), the length of the coil is inversely proportional to the magnetic flux and hence it decreases with increase in length as shown in Fig. 5.

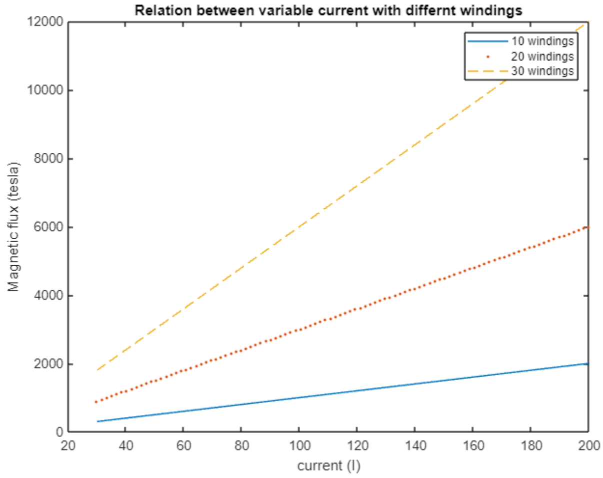

Fig. 4. Magnetic Flux vs Current

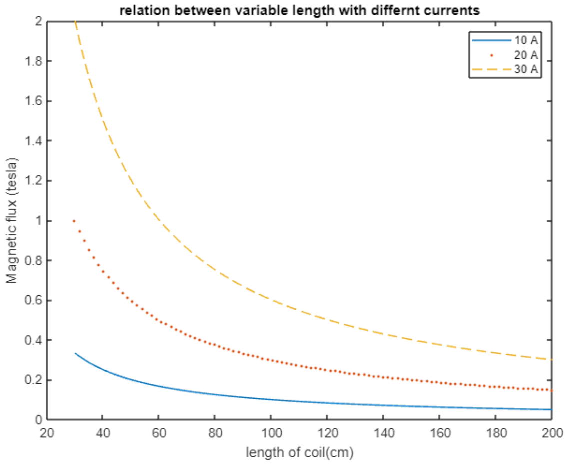

Fig. 5. Magnetic flux vs length of coil

Thus, when the magnetic flux increases with number of windings of the coil, it means that the number of field lines are increased, which cause much denser region of field lines which in turn increases adhesive strength. Apart from these factors, arrangement and alignment of the electromagnets will also contribute to the magnetic adhesive force. This work introduces array, square and diamond shaped arrangements that increase the magnetic flux produced and hence the magnetic adhesion.

Soft iron was considered for experimentation purpose with 36 AWG copper wire as winding coil. 36 AWG is approximately 0.1 mm thickness. The number of windings assumed is 5000, which is feasible with 0.1 mm thickness of coil. Different electromagnet arrangements have been analyzed to increase the electromagnetic adhesion force. The range of magnetic flux densities can be inferred from Fig. 6.

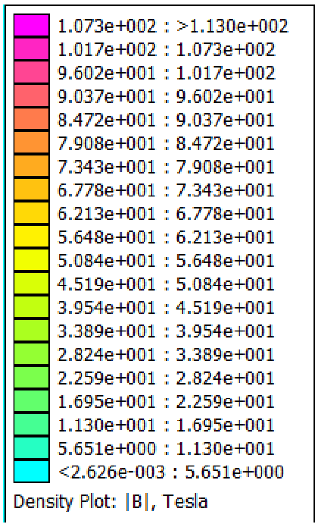

Fig. 6. Magnetic flux densities and their corresponding color notations.

A. Square Formation

4 electromagnets were considered with 5000 windings of copper coil, and the alignment of the electromagnets are specified by the arrow marks where arrow represent North Pole and tail represent South Pole. Initially, a 50A current was passed though coils which generated a minimum flux around it. Here, the center of the arrangement is studied hence it provides the maximum magnetic adhesion against the weight of the WCR. The magnetic flux produced is approximately 6 T which accounts to 4.6 N of force. Higher values of force can be obtained by passing higher values of current, usually at an order of 100 A.

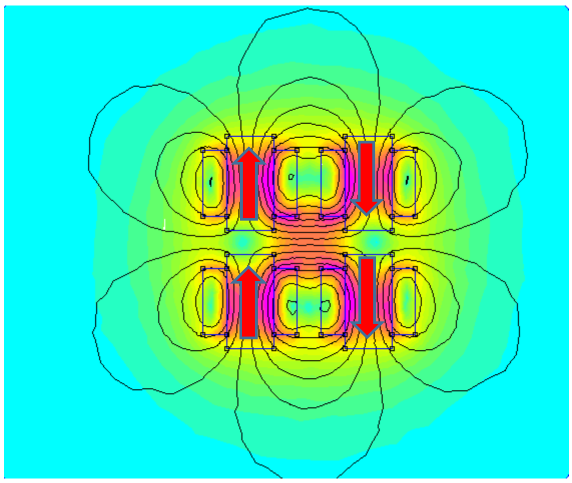

Fig. 7. Magnetic Flux produced due to square arrangement

With gradual increment in current supply the force created is ~60N that is more than sufficient for the robot of 2 kg to adhere to the wall. This is made in reference with [6], where 35 N was sufficient to move a robot against gravity over the wall.

B. Diamond Formation

Fig. 8 shows the diamond formation and the corresponding magnetic flux produced when 50 A current is passed. The direction in which the magnets are placed is as shown in the figure.

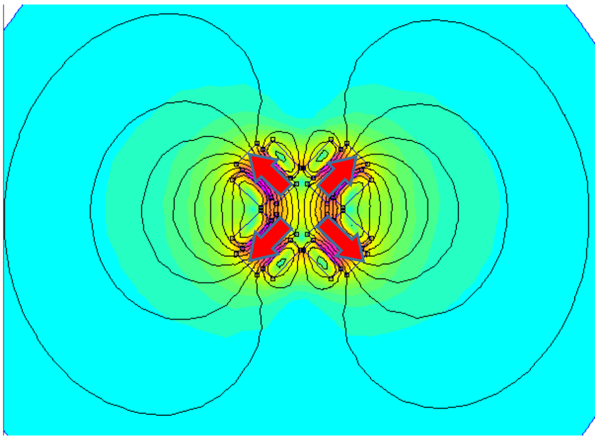

Fig. 8. Magnetic flux in diamond formation

The force created is 3.9 N at the center which is less than square arrangement and it is not capable of holding the WCR on the wall.

C. Array

It was the one formation with permanent magnets (Halbach array) [3] which produces the highest magnetic field strength based on the magnets. Thus, this formation is also tested with electromagnets to find the maximum amount of force obtained again the substance to withstand the WCR without sliding or toppling. 4 electromagnets were taken and arranged in an array fashion, next to each other as shown in the Fig. 9.

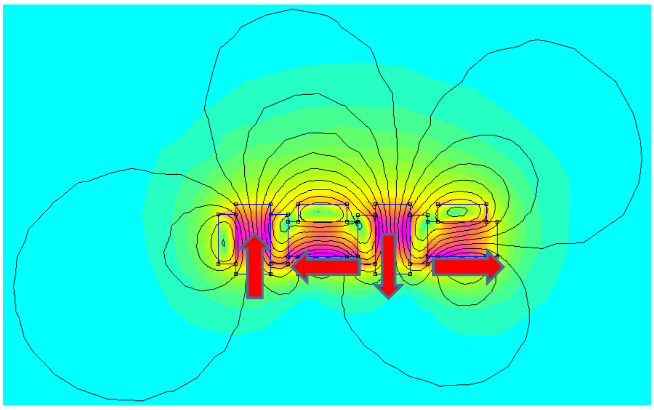

Fig. 9. Array formation using electromagnets

This formation gives the highest adhesive force approximately ~150 N on the surface, for a current of 50 A. It reaches to around 600 N when a current of 500 A is passed through the coil. Thus, it can be concluded that the arrangement in the form of array creates greater adhesion force than square and diamond arrangements. It can keep the WCR adhered to the wall without sliding or toppling. It can be inferred from Table 1 that the force created by the array is approximately 50 times more than the square and diamond formation hence it is the most suitable arrangement to achieve sufficient magnetic adhesion with just 50 A of current. This is due to the fact that the area of concentration of magnetic flux at the center of bot square and diamond is very less whereas in the array formation, the area of concentration of magnetic flux includes the whole arrangement.

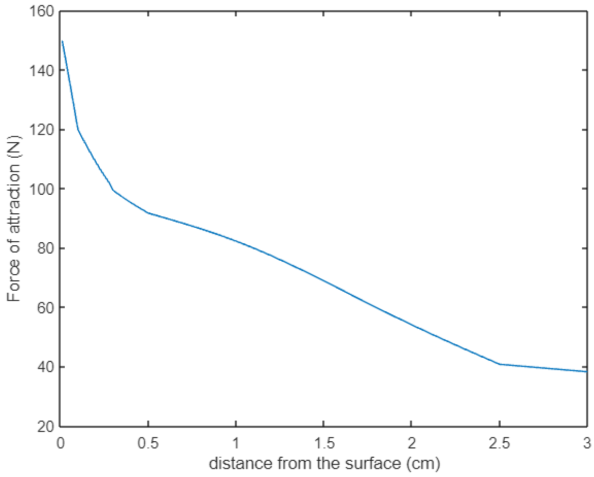

Fig. 10. Magnetic force vs distance between electromagnets and surface

Besides, a relationship between the electromagnetic force and the distance between the electromagnets and surface has been determined. To conduct this analysis, an iron substance i.e., rectangular shaped plate was placed above the Halbach array configurations in FEMM. For distances between the electromagnets and the surface in the range [0.01,3] cm, the force exerted to the ferromagnetic substance was computed. Fig. 10 depicts the analysis results.

Referring to Fig. 1, it could be noted that the x axis of Fig. 10 is given in cm. The range has changed since 4 magnets are used instead of one, which in turn increases the magnetic strength and hence toppling does not happen till the distance is at least 1.5 cm. When the distance between the metal sheets and the magnetic arrangements goes beyond 1.5, the force of attraction starts decreasing and there is a fair chance that the WCR topples when the distance is 2 cm. This also proves that using number of magnets instead of 1 in array fashion increases the magnetic adhesion.

The largest force of attraction is achieved when ferromagnets are placed close to each other and the distance between the surface and ferromagnetic arrangement is less. The WCR's operating range will be between [0.5,1] cm from the surface, which delivers roughly 100N of force.

TABLE I. COMPARISON OF MAGNETIC FLUX AND FORCE CREATED FOR DIFFERENT METHODS OF ADHESION. CURRENT I = 50 A

Types of Adhesion		Magnetic Flux (Tesla)	Force (N)
Suction adhesion by suction chamber		-	35
Magnetic adhesion (Electro magnets)	Square	6.146	4.6
	Diamond	4.117	3.9
	Array	8.142	149.2

IV. CONCLUSION

In order to perform various day-to-day applications, WCRs are becoming necessary to avoid catastrophic events and loss of human lives. Various patterns of electromagnets to achieve exclusive magnetic adhesion has been discussed in this work. The arrangements such as square, diamond and array, with 5000 turns of 36 AWB copper coil, are studied and it has been inferred that the array produces ~150N.This is very high compared to square and diamond arrangements that contribute to around ~5 N. For a 2 kg WCR to be lifted against gravity, just 35 N of force would suffice which can be produced by suction chamber. Since the electromagnetic adhesion generated by the array 4 times the required adhesion force, it is more suitable for adhesion in metal surfaces and to maintain the stability without sliding even while encountering obstacles. In future, a combination for suction chamber and electromagnets can be carried out in order to maintain complete stability over normal as well as metal surfaces.

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