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The Electric Origin of Magnetic Forces Theory: General Framework

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ABSTRACT This paper presents the first general framework to explain the magnetic force as a result of electric force interactions between current charges moving at any constant speed and combination. The explanation depends on analyzing the spreading electric field in the space and the movement of charges inside current elements. Previous work used special relativity to describe the magnetic force as an electric one, but this description contradicts the fact that electrically neutral wires stay neutral with or without current flowing through them, as well as, it does not facilitate the derivation of the infinitesimal laws of magnetism. In this paper, the provided explanation is proved by deriving the infinitesimal magnetic force law and Biot-Savart law using the basis of electric forces. This work lies at the intersection between Electrical Engineering and Physics, and it is important to understand what is magnetism and its origin. Such understanding may help engineers and scientists in making new advancements in magnetic materials and applied magnetic technologies.

INDEX TERMS Magnetism, magnetic force, electric force, electromagnetic fields, electromagnetism, charge, current, monopoles, magnetic charge, Biot-Savart law, fundamental forces.

I. INTRODUCTION

Magnets have amazed humanity since their discovery by their force to move things without touching them. For example, a magnet can lift several metal rings and super-cooled magnets can float over a magnetized track. This powerful force is related to the motion of electric charges, therefore fast charged objects with large electric charges produce a greater force to move other magnetic objects. While scientists do understand how the magnetic force acts, they are not really sure why it exists. Why are moving charges producing it? What is the used mechanism to produce them? Why are moving charges affected by it only? Why magnets always occur in the form of dipoles, i.e., there is always a North pole and a South pole to a magnet? Do monopoles, i.e., isolated "north" and "south" poles of a magnet, exist? These are questions that scientists and engineers cannot answer with our current understanding of physics. Answering these questions may help engineers in making advancements to the technology and applications of magnetism and magnetic materials.

The magnetic force has been considered different in origin from the electric force between charges since its discovery, i.e., when Oersted found that a current-carrying wire generates a force on a magnetized compass needle. That is because current-carrying wires are intrinsically charge-neutral [1]. This force was further studied by Biot and Savart who found that every current-carrying wire generates a magnetic field around it. The strength and direction of this field are related to the magnitude, direction, length, and proximity of the electric current. This magnetic field produces a force on any electric charge moving in it according to Lorentz force law [2]. Then, Ampere found that the integrated magnetic field around a closed loop is related to the electric current passing through the loop. Later on, Faraday discovered the electromagnetic induction, which describes the connection between electricity and magnetism, i.e., a time-varying magnetic field is always accompanied by a spatially varying electric field. Then, Maxwell published his equations that mathematically unify the laws which govern the observed electric force and magnetic force. The unified laws describe how these forces are generated by charges, currents, and changes in the fields, but none of them specifies the origin of these forces [3]. Since then, electricity and magnetism have been treated more and more as different aspects of the same subject [4]–[7]. An early attempt to explore the origin of the magnetic force used relativity and Lorentz contraction to explain the magnetic

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force as an electric one between long wires carrying currents [2], [8], [9]. This explanation suffers from major problems [10] and the magnetic force is proved to not be a relativistic effect [11]. In 1997, an effort was made by Johnson [12] to unify the origin of electricity and magnetism. However, the work ended up yielding a formula that is unequal to the well-known magnetic force law. Another attempt used Quantum Physics to explain magnetism by virtual photons, i.e., infinitesimal imaginary particles interacting with each other at a distance [13]–[17]. These photons create electric and magnetic fields that are responsible for the interaction between charged objects. But these virtual photons are composed entirely of math and exist only to fill the gaps in physics such as the origin of the magnetic force. Furthermore, the Grand Unified Theories predict the existence of magnetic monopoles [18]–[25]. Monopoles have never been observed. This is because either there is not a powerful enough particle accelerator or physicists could be wrong about how the universe and magnetism work.

In this contribution, the first general framework to explain the electric origin of the magnetic force produced by direct currents is presented, i.e., the mechanism of ''How'' electric charges moving at a constant speed produce the observed magnetic field and force through the changes in their electric field spreading in the space due to their movement. It explains the observed magnetic force as the net force applied to a current element due to the electric interaction between the moving charges generating the currents. These charges are able to move at any constant speed and combination. The explanation provides a model for the movement of charges inside current elements and provides an analysis for the electric field spreading in the space due to this movement. The provided explanation is relativistic invariant and it is fully consistent with the electromagnetic theory. This explanation is proved by deriving the infinitesimal magnetic force law and Biot-Savart law using the basis of electric forces as specified in the electromagnetic theory. Biot-Savart law is used for this proof because it can be obtained from Ampere's law and Maxwell's equations for magnetic fields generated by direct currents or none accelerating moving charges. The analysis for applying this explanation for a special case of currents, i.e., currents that are characterized as equal amounts of positive and negative hypothetical point charges moving in opposite directions at the speed of light, has been published in [10]. These hypothetical point charges as stated in the third postulate in [10] are used in that paper for modeling purposes to gain new insight from a different perspective about magnetism. Using them has simplified the analysis of the electric field because all objects are moving at the same speed which is the speed of light, i.e., the hypothetical charges are moving at the same spreading speed of the electric field in the space. Having all objects moving at the same speed allows defining a 3D space with its infinitesimal elements, which satisfy the following two criteria: (1) Ability to track the movement of any object through all the infinitesimal points forming its path, and (2) Allowing to define infinitesimal electric current elements where charges are continuously flowing crossing the element's surface to generate the current. Defining such a space is challenging when having objects moving at different speeds. There is no trivial solution for it, what is trackable in one speed may not be trackable in another [26], [27]. This issue is addressed in this paper. The main contribution of this paper is expanding the electric field analysis in [10] to be applied for currents generated by charges moving at any constant speed, i.e., less than or equal to the speed of light, and by any combination. This expansion provides a general framework to apply the electric origin of magnetic forces theory to different types of direct currents. The framework defines a 3D space with its infinitesimal elements for point, current, time and length, such that it facilitates tracking electric field changes in the space due to charges moving at different speeds. This work lies at the intersection between Electrical Engineering and Physics. This work is important to answer the questions about ''What is Magnetism'' and the existence of monopoles, which are one of the top unsolved problems in physics.

This paper is organized as follows: Section (II) provides background information that is needed to understand the terminology of this work and to interpret the results. Section (III) reviews related works in this area. Section (IV) describes the electric origin of the magnetic force. Section (V) concludes the paper with a summary of the work and its impact on the current state of the research in this field.

II. BACKGROUND

This section provides background information on discontinuity charges that is needed to understand the terminology of this work and to interpret the results.

The discontinuity charge term refers to the electric charge that exists at the points, where the electric field changes its value or direction due to a change in the charges generating it, either in the value, position, or both. It was introduced by Shadid [10] to explain the magnetic force as a purely electric one. In that work, an infinitesimal current element that is electrically neutral is modeled by equal amounts of positive and negative hypothetical point charges moving in opposite directions at the speed of light, denoted by c. This speed has been chosen for these hypothetical charges to simplify the analysis, and to make sure their movement is seen the same by any observer at any position in the space, and at any time or frame. For example, in a current element as shown in figure (1 a), the current is propagating from right to left, so negative charges move from left to right and the positive charges move from right to left to cross the central surface to generate the current.

The production of discontinuity charges by current elements is explained as follows. Let $T = \{t_0, t_1, t_2, \ldots, t_i, t_{i+1}, \ldots\}$ be a set of consecutive continuous time moments such that $t_{i+1} = t_i + dt$, where i is the index of the moment t_i in the set T, and dt is an infinitesimal time interval at which the current is seen flowing in a current element. Each moment t_i represents the events occurring in the current element to

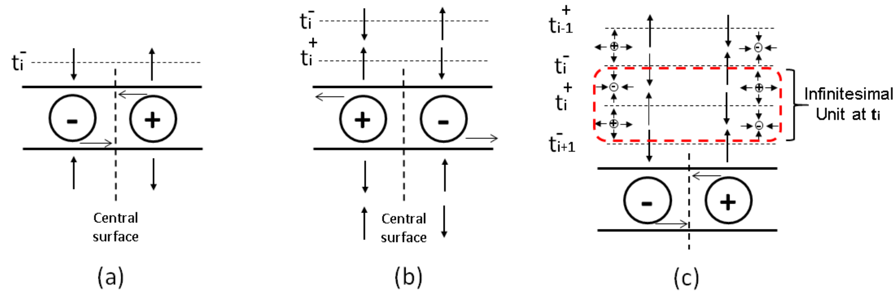

FIGURE 1. **Shows the electric field spreading through space for a current element due to the movement of positive and negative charges, as well as, the discontinuity charges, and the generated infinitesimal unit at t_i.**

generate the current during dt from $t_i - \frac{dt}{2}$ to $t_i + \frac{dt}{2}$. Let t_i^- be a moment approaching t_i from the left side and representing the events occurring during $[t_i - \frac{dt}{2}, t_i)$, while t_i^+ be a moment approaching t_i from the right side and representing the events occurring during $[t_i, t_i + \frac{dt}{2})$. For the moment t_i, the motion of the charges is modeled as follows. At t_i^- the positive charge is in the first half on the right side of the current element's space moving toward the left half. Meanwhile, the negative charge is in the second half on the left side of the current element's space, moving toward the right half; see figure (1 a). At t_i^+, the positive charge changes its position to the second half on the left side of the current element's space, moving to exit the current element from the left. Meanwhile, the negative charge changes its position to the first half on the right side of the current element's space, moving to exit the current element from the right; see figure (1 b). The moving charges are seen at two positions only inside the infinitesimal current element at any moment and not seen outside. These charges switch their positions around the central surface to perform the crossing process to generate the current during dt. So, at moment t_i^-, the positive charge in the right half emits an outward electric field, and the negative charge at the left half emits an inward electric field; see figure (1 a). At moment t_i^+, after the position switching, the negative charge in the right half emits an inward electric field, and the positive charge at the left half emits an outward electric field; see figure (1 b). These changes in the electric field spread through space at the speed of light in all directions and decrease in intensity at $1/r^2$ because there is no acceleration, i.e., the current charges are moving at a constant speed c. When this continues for a while, these changes in the electric field form a pattern spreading in the space to indicate the movement of charges to generate the current as shown in figure (1 c). This spreading pattern is assumed to be always seen the same with no change by any observer at any position in the space at any time, otherwise, a fixed current would have different directions at different points in the space, and this is not true.

The generated pattern of changes in the electric field, i.e., from inward to outward and outward to inward, due to charge movements indicates a discontinuity in the electric field spreading in the space. Following Gauss' law and

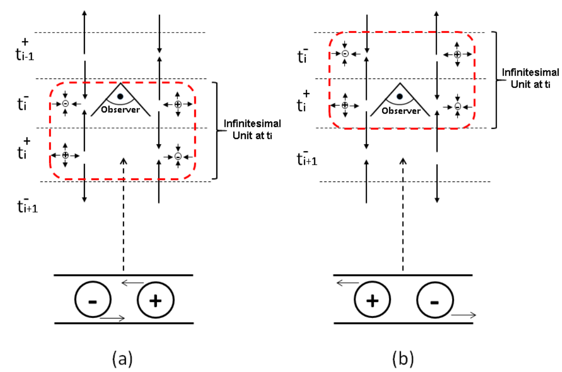

FIGURE 2. **Shows the interaction of an observer in the space with an infinitesimal unit that contains discontinuity charges generated by an infinitesimal current element at t_i.**

assuming constant permittivity, ϵ, this discontinuity in the electric field indicates the existence of an electric charge [28]. This charge is called a discontinuity charge. Figure (1 c) shows discontinuity charges produced by a current element. So, at every moment t_i, a current element produces two pairs of discontinuity charges: The first pair indicates the movement of charges by switching positions to generate the current, while the second pair indicates the movement of charges to exit the current element and the entrance of new charges. Notice that the first pair are at discontinuity points between electric fields generated completely by the charges inside the current element at moment t_i. These two pairs travel together to transmit the image of their current element and the movement of its charges to every point in the space. These two pairs are assumed to be contained together in one infinitesimal unit that is traveling the space so the current is seen the same by any observer at any position in the space. This infinitesimal unit is assumed to completely interact with every point in the space, i.e., each point interacts with the two pairs contained in the infinitesimal unit. Figure (2) shows an example for an observer experiencing the effect of the discontinuity charges generated at moment t_i^- and t_i^+ by positive charges moving from right to left and negative charges moving from left to right inside a current element at t_i. The observer interacts first with the discontinuity charges produced by the movement of charges to switch positions to generate the current, then it interacts with the discontinuity charges produced by the movement of charges exiting the current element and the entrance of new charges. These infinitesimal units can be explained by the photons that exert electric forces and travel through space at the speed of light to indicate the movement of charges and the corresponding changes in the electric field [29]–[31]. Further investigation is needed to explore the nature of the electric charge and the effect of charge movements into space. This investigation may need to be conducted in connection with other explorations to the nature of gravity and nuclear forces within a unified framework, e.g., string theory [32]–[34]. Such an investigation is not part of this work and is better suited for future research.

III. RELATED WORK

Four attempts were found either to tie the laws of magnetism and electricity or to explain the magnetic force as purely electric: (1) Maxwell's equations and the electromagnetic field tensor [3], [35], (2) Lorentz length contraction approach [2], [8], [9], [36], (3) retarded action approach [12], and (4) the electric origin of magnetic force theory [10].

Maxwell's equations are a set of formulas that mathematically describe the laws governing electromagnetic forces, i.e., the electric force and the magnetic force, without specifying their origin [35], [37], [38]. They unify experimental laws, i.e., Ampere's law and Faraday's law, into a symmetric set of coherent equations. On the other hand, the electromagnetic field tensor is a mathematical representation that rewrites Maxwell's equations and the Lorentz force law in a form that is invariant under Lorentz transformations [39]. Although these equations tie the electric field and magnetic field laws together, they treat the magnetic field as different in origin from the electric field, as well as, they do not specify how moving charges produce the magnetic field [38], [40].

The Lorentz length contraction approach describes the magnetic force as a natural consequence of special relativity and purely electrostatic forces [2], [8], [9], [36]. This approach considers infinite parallel current-wires only. The approach analyzes the force between two parallel wires in two frames: the ions rest frame and the electrons rest frame. Using the Lorentz transformation, in the ions rest frame, the force appears as purely magnetostatic, while in the electrons rest frame, the force appears as a combination of magnetic and electric forces. There are three shortcomings for this approach: (1) the force is not explained as purely electric in all rest frames, (2) it applies only for infinite wires and does not apply for infinitesimal elements, so it does not facilitate the derivation of the infinitesimal magnetic force law and Biot-Savart law, and (3) it contradicts the fact that an electrically neutral wire continues to stay neutral in the lab frame with or without having a current flowing through it. It assumes that the density of the charges in a wire changes according to their speed because of the change in their sizes according to Lorentz length contraction. So, an electrically neutral wire with no current flowing is not going to stay neutral when the electrons start moving to generate a current and this is not true. Moreover, Jefimenko [11] concludes that neither the electric field nor the magnetic field is a relativistic effect. If the interaction between moving electric charges is due to the magnetic field completely, then the same relativistic force transformation equations make it unavoidable that the electric field is also present.

The retarded action approach explains the magnetic force between two current elements as a result of the inhomogeneous propagation of the electric field from different parts of continuously distributed moving charges in a conductor [12]. This inhomogeneous propagation causes a net difference between the field from the moving electrons and the immobile ions in a conductor. The drawback of this approach is for two straight conductors carrying currents, the force law between them is not equal to the well-known magnetic force law as stated by the author.

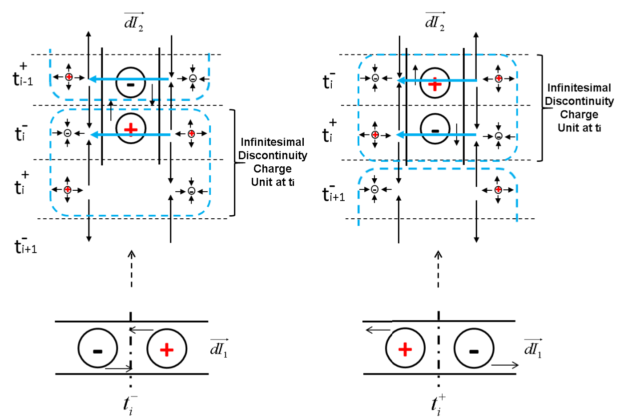

FIGURE 3. Shows an example of the interaction between an infinitesimal discontinuity charge unit and the charges of a current element present at a crossing point in the space.

The electric origin of magnetic force theory provides a successful explanation for the magnetic force as a purely electric one that facilitates the derivation of its law [10]. It characterizes a current as equal amounts of positive and negative hypothetical point charges moving in opposite directions at the speed of light. Then it analyzes the changes of the spreading electric field in the space and the generated infinitesimal discontinuity charge units due to the movement of charges inside current elements. These units travel the space interacting with the charges of current elements that are present at the points they are crossing in the space, for example, see figure (3). This interaction produces a force on the current element. This force is proportional to the current charges produced the infinitesimal discontinuity charge unit, and to the current charges present at the crossing point in the space as specified in equation (1) [10].

$$\overrightarrow{dF_{12}} = \frac{1}{4\pi\epsilon}\frac{dQ_1\, dQ_2}{|\overrightarrow{r}|^2}(\overrightarrow{a_2} \times \overrightarrow{a_1} \times \overrightarrow{a_r}). \qquad (1)$$

where $\overrightarrow{dF_{12}}$ is the force felt by the current element at the crossing point, denoted by 2, due to the current element that produced the interacting infinitesimal discontinuity charge units, denoted by 1. dQ_1 and dQ_2 are the amounts of charges producing the currents inside elements 1 and 2, respectively. $\overrightarrow{a_1}$ and $\overrightarrow{a_2}$ are unit vectors indicating the directions of the current propagation in elements 1 and 2, respectively. $\overrightarrow{r}$ is the distance vector pointing from current element 1 toward current element 2. $\left|\overrightarrow{r}\right|$ and $\overrightarrow{a_r}$ are the amplitude and the unit direction of the distance vector, respectively. The work then rewrites equation (1) to equation (2) by substituting for dQ_1 and dQ_2 using their relation to currents running in their corresponding elements.

$$\overrightarrow{dF_{12}} = \frac{\mu}{4\pi} \frac{I_1 I_2}{\left|\overrightarrow{r}\right|^2} dl\, dl\, (\overrightarrow{a_2} \times \overrightarrow{a_1} \times \overrightarrow{a_r}) \tag{2}$$

where I_1 and I_2 are the amounts of current running in current elements 1 and 2, respectively. dl is the infinitesimal length of a current element. Notice that equation (2) is an exact equivalent to the well-known magnetic force law.

This explanation has been developed for a special case where current charges are moving at the speed of light, but it is concluded that the magnetic force is purely electric because of the fact that regardless how currents are generated as long as they have the same amount and direction they produce the same magnetic effect in the space. Despite this fact, this explanation will not be general without addressing currents generated by charges moving at a speed other than the speed of light or by a single type of charge. These two cases are resolved in this paper.

IV. METHODOLOGY

This section describes the electric origin of the magnetic force for direct currents generated by charges moving at any constant speed, i.e., there is no acceleration, that is less than or equal to the speed of light. The electric origin of the magnetic force produced by these currents is studied by analyzing the electric field and its changes spreading in the space due to the movement of electric charges inside the current elements. In this analysis, the current elements are two types: source and destination. The source element contains moving charges that generate the electric field spreading in the space. The destination element contains moving charges that interact with the spreading electric field. The analysis is performed on currents produced by moving positive and negative charges in opposite directions at the same speed to simplify the presentation in this paper. This analysis is applicable for currents generated by moving positive charges, by moving negative charges or by both moving positive and negative charges at different constant speeds as shown at the end of this section.

The analysis process requires defining a 3D space, infinitesimal points, and infinitesimal current elements, as well as, building a model to represent current charges and their movement inside a current element. The 3D space is defined by three orthonormal unit vectors $\overrightarrow{u_1}$, $\overrightarrow{u_2}$, and $\overrightarrow{u_3}$, such that any element in the space is decomposed into its three perpendicular components. Each component is analyzed separately along with its own axis. For each axis, an infinitesimal point in the space is defined as a 3D square shape that is smaller than any non-infinitesimal one, i.e., nothing can be measured smaller than it. An infinitesimal current element consists of two touching infinitesimal points such that the touching area between them is the crossing surface for the current charges, refer to figure (5). Notice that there is no surface inside an infinitesimal point. A current is generated in a current element by having a charge crossing the surface between the two infinitesimal points during an infinitesimal time dt, such that the charge is seen occupying each point for $dt/2$. The infinitesimal length for a current element is denoted by dl. The relationship between dl and dt is determined by the maximum hypothetical possible speed for a charge and the traveling speed for electric field changes in the space which is the speed of light, c, as specified in equation (3).

$$dl = c\, dt \tag{3}$$

Equation (3) defines dl by the minimum length needed to observe the moving charges generating the current at the two sides of the surface during dt. The model uses this definition for two reasons:

1) Having a unified analysis space that handles current elements generated by charges moving at any speed,
2) Satisfying the fact that a continuous current is continuously seen generated in the current element during dt from any point in the space.

These two reasons are important to satisfy the fact that a constant current is seen the same at all points in the space, otherwise, the defined 3D space with its infinitesimal elements will not be valid.

For the first reason, the analysis for current element interactions must be conducted using a space that satisfies the definition of the current regardless of how it is generated. According to the definition of the current, a charge crossing a surface must be seen at the two sides of that surface during dt. The minimum infinitesimal length for a current element that satisfies this definition regardless of the speed is the one specified in equation (3). Otherwise, if dl is related to dt by speed v, i.e., $dl = v\, dt$, that is less than the speed of light, i.e., $v < c$, current charges moving at a speed higher than v are seen on one side of the current element at t_i^- and not on the other side at t_i^+, i.e., they moved outside the current element, which is against the definition of the current that charges are seen at both sides of the surface. Charges outside the current element are assumed to have no effect as they do not exist.

For the second reason, continuous currents are modeled by moving charges that continuously cross the surface of a current element. This crossing is modeled by having the moving charges change their positions around the surface, refer to section (II). This change in position generates a change in the electric field that is spreading in the space. This change in the electric field travels the space at the speed of light indicating the movement of charges around the surface. If dl is related to dt by a speed v less than the speed of light, there is a chance for an observer at an infinitesimal point in the space to see no changes in the electric field for some time during dt, which indicates that the current charges have stopped moving and crossing the surface for some time so no current has been generated, and this is against the definition of continuous currents. Hence the use of c in equation (3). Figure (4) shows an illustrative snapshot for the electric field spreading in the space due to the movement of current charges inside a source current element at time t_i at a speed $v = c/5$. There are seven current elements shown in the snapshot referred to as $e_1, e_2, \ldots, e_7$. The changes in the electric field are observed at two infinitesimal points only: the upper infinitesimal point of e_3 and the lower infinitesimal point of e_5. While the other infinitesimal points do not see any change in the electric field, which indicates that the charges are still and not crossing the surface to generate the current, and this is not right.

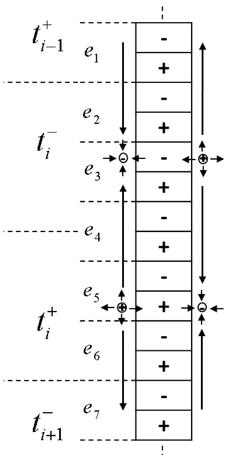

FIGURE 4. Shows an illustrative snapshot for the distribution of the discontinuity charges around a segment of seven infinitesimal current elements, e_1 to e_7, in the space when dl is related to dt by a speed that is 5 times slower than the speed of light, i.e., $dl = \frac{c}{5} dt$.

For currents generated by charges moving at a speed less than the speed of light, the charge movement inside a current element crossing the surface from one side to the other one can be explained by assuming the charge is gradually crossing the surface. So part of the charge is going to switch sides around the surface by being on one side at t_i^{-}, then it is on the other side at t_i^{+}, while the remaining parts of the charge do not change sides, i.e., their movement is not enough to cross the surface at t_i. The amount of charge that each part holds is $\frac{v}{c}\,dQ$. The parts that are crossing are assumed to be occupying the region that is $\frac{v}{c}\frac{dl}{2}$ distance from the crossing surface within the infinitesimal point to cross the surface at a speed v, refer to figure (5).

The current is modeled to be generated by positive and negative charges of the same amount crossing the central surface at the same speed $v = |\overrightarrow{v}|$ in opposite directions. This speed is assumed to be constant, i.e., no acceleration. Crossing the central surface in this model means that, at any

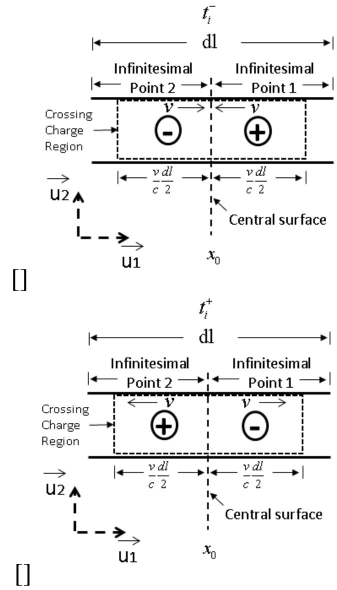

FIGURE 5. Shows how the current is modeled inside an infinitesimal current element with a current propagating in the negative $\overrightarrow{u_1}$ direction at t_i.

time t_i and infinitesimal time dt, the current charges switch their positions around the surface to generate the current, refer to figure (5). In this figure, at t_i^{-}, the net positive charge is on the right side of the central surface while the negative charge is on the left side. At t_i^{+}, the charges change their positions, the net positive charge is on the left side of the central surface while the negative charge is on the right side. Each change in position for current charges produces a change in the electric field that forms an infinitesimal discontinuity charge unit as described in section (II). These units are continuously generated, i.e., one after another, by a source element as long as the current is continuously flowing in it. The amount of current charges crossing the central surface of the source element generating a discontinuity charge unit denoted as dQ_1, is computed in equation (4).

$$dQ_1 = I_1\,dt = I_1\,\frac{dl}{c} \tag{4}$$

where I_1 is the amount of the current flowing in the source element. The infinitesimal discontinuity charge units spread in the space in all directions at the speed of light and interact with the charges crossing the central surface of a destination current element at each point in the space if any. The amount of current charges crossing the central surface of the destination element and interacting with a discontinuity charge unit during its crossing denoted as dQ_2, is computed in equation (5).

$$dQ_2 = I_2\,dt = I_2\,\frac{dl}{c} \tag{5}$$

where I_2 the current flowing in the destination element. The movement of current charges in the destination element is modeled in a way similar to the one done for the source element.

The general formula for the amount of the electric force, i.e., the amplitude of the force without the cross product of the unit vectors, produced on a destination current element due to the interaction of its moving charges with the surrounding discontinuity charges is shown in equation (6).

$$\left|\overrightarrow{dF_{12}}\right| = \frac{1}{4\pi\epsilon}\frac{dQ_1\,dQ_2}{|\vec{r}\,|^2}. \tag{6}$$

where $\left|\overrightarrow{dF_{12}}\right|$ is the amount of force produced by a destination element due to the existence of the source element. This formula is obtained from equation (1) by removing the cross product part.

Equation (6) is rewritten to equation (7) by substituting dQ_1 and dQ_2 by their formulas specified in equations (4 and 5), respectively.

$$\left|\overrightarrow{dF_{12}}\right| = \frac{1}{4\pi\epsilon}\frac{I_1 I_2}{|\vec{r}\,|^2}\frac{dl}{c}\frac{dl}{c}. \tag{7}$$

Equation (7) is simplified further as shown in equation (8) because $\mu = \frac{1}{\epsilon c^2}$.

$$\left|\overrightarrow{dF_{12}}\right| = \frac{\mu}{4\pi}\frac{I_1 I_2}{|\vec{r}\,|^2}dl\,dl. \tag{8}$$

By adding the cross product of the unit vectors, the final formula for the force affecting the destination element due to the existence of the source element is shown in equation (9).

$$\overrightarrow{dF_{12}} = \frac{\mu}{4\pi}\frac{I_1 I_2}{|\vec{r}\,|^2}\,dl\,dl\,(\vec{a_2}\times\vec{a_1}\times\vec{a_r}). \tag{9}$$

Equation (9) is an exact equivalent, in both magnitude and direction, to the well-known magnetic force law between two parallel filamentary current elements.

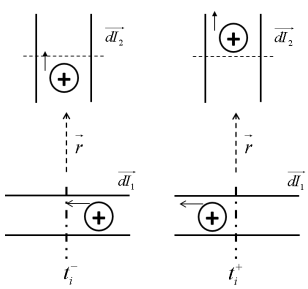

FIGURE 6. Shows two filamentary current elements at a perpendicular position with currents generated by moving positive charges.

For currents generated by either positive or negative charges, the analysis is performed in two steps, one for the source element and the other one for the destination element. In this work, the analysis is shown for a single case to avoid redundancy. Let $\overrightarrow{dI_1} = I_1\,dl\,\vec{a_1}$ and $\overrightarrow{dI_2} = I_2\,dl\,\vec{a_2}$ be a source current element and a destination current element, respectively, that are perpendicular to each other and have currents generated by moving positive charges as shown in figure (6).

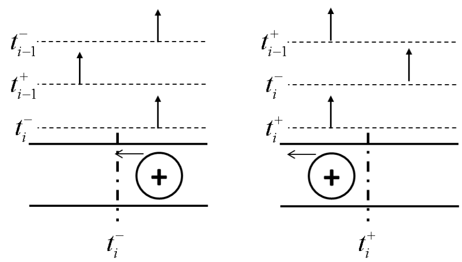

FIGURE 7. Shows the electric field changes spreading in the space in one direction due to the movement of the positive current charge.

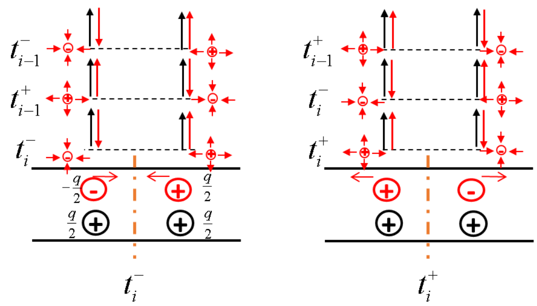

FIGURE 8. Shows a model for a current element that is generated by a positive charge moving toward the left direction. The model represents this moving charge by two static charges (black) and two moving charges (red).

The current is modeled in each element by a single positive charge crossing the central surface of the current element, such that at any time t_i, the charge is on one side at t_i^- and on the other side at t_i^+. The current is assumed to be flowing from left to right in the source element and from bottom to top in the destination element.

For the source element, the changes in the electric field spreading in the space due to the movement of the charge is shown for one direction in figure (7). When the positive current charge is on the right side of the central surface at t_i^-, it emits an outward electric field in the upper direction for $dt/2$ while nothing is emitted from the left side because there is no charge there. Then at time $t_i^+$the charge changes its position to the left side of the surface and emits an outward electric field in the upper direction for $dt/2$ while nothing is emitted from the left side. This movement of the charge is modeled using two static charges and two moving charges as shown in figure (8). Each charge has half the amount of the original charge. The two static charges are positive, i.e., similar to the type of the original current charge, and they are placed at the two sides of the surface, one on each side. These charges are responsible for the observed static electric field. The moving charges are a positive charge and a negative one moving in opposite directions at the same speed as the original charge. These charges are responsible for generating the infinitesimal discontinuity units to indicate the charge movements inside the current element. These units travel the space and interact with other current elements. This interaction is similar to the

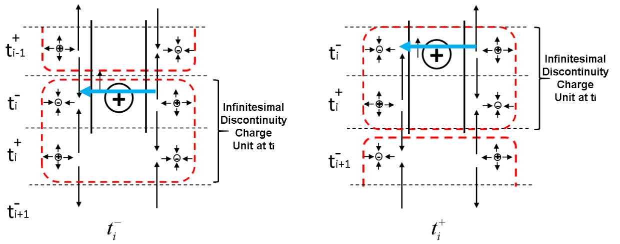

FIGURE 9. **Shows the interaction of a destination current element generated by a positive moving charge with a crossing infinitesimal discontinuity charge unit at t_i.**

one described earlier for currents generated by positive and negative charges of the same amount moving in the opposite direction.

For the destination element, the interaction of the positive charge with the crossing discontinuity units is shown in figure (9). At t_i^-, the positive charge interacts electrically with the discontinuity charges surrounding it. This interaction produces a force on the positive charge toward the left that is perpendicular to the current element and the current direction. The positive charge pushes the current element with this force because it is prohibited to leave the current element [10]. At t_i^+, the positive charge changes its position to the other side of the central surface, as well as, the discontinuity charges change their positions to cross the destination current element. The distribution of the discontinuity charges around the positive charge at this moment is similar to the one was at t_i^-. So the same electric force is produced on the positive charge, and the same push is applied to the current element. According to equation (6), this applied force on the current element is an exact equivalent, in both magnitude and direction, to the magnetic force observed on this current element due to the existence of a source element. If the charge is static, i.e., not moving, then the distribution of the surrounding discontinuity charges at t_i^+ is opposite to the one was at t_i^-. So a force of the same amount but in the opposite direction is applied on the charge canceling the effect of the one applied at t_i^-. Hence the net force applied to the charge at t_i is zero according to equation (10).

$$\overrightarrow{dF_{12}}\,dt = \overrightarrow{dF_{12}^{i-}}\,\frac{dt}{2} + \overrightarrow{dF_{12}^{i+}}\,\frac{dt}{2}, \tag{10}$$

For currents generated by a combination of multiple charges running at different speeds, the superposition principle is applied to find the net response caused by them.

The electric origin of the magnetic force theory defines the magnetic force as the net force applied on a current element due to the electric interaction between the moving charges inside the element and the surrounding discontinuity charges. This net force is either non-zero or zero. The net force is non-zero on the current element when the exerted forces on its moving charges are perpendicular to the current element and push it in the same direction. However, the net force is zero when these charges push the current element in opposite directions thereby canceling each other or when the exerted forces on the current charges are completely along the direction of their movement along the current element [10]. The discontinuity charges exist at the discontinuity points of a spreading electric field generated by a moving charge in the space. These discontinuity points represent changes in the electric field to indicate the movement of the charge generating the electric field.

This theory indicates that regardless of how currents are generated, as long as they produce the same discontinuity charges, the same magnetic force is obtained, and this is consistent with the magnetic force properties. This suggests that if the electric effect in the space of a moving charge is artificially altered such that it is equivalent to a static field produced by a static charge, no magnetic force will be observed due to this movement.

This theory helps in providing an explanation for the magnetic force properties. For example, it explains why the magnetic field is circular, i.e., forming a closed loop, as stated in Maxwell's equations so no monopole exists [41], how a moving charge produces a magnetic field around it, and why an electric charge feels the effect of the magnetic field when it is moving, and how it does not feel that field when it is static. Also, it provides an answer to the controversial question of how Newton's third law is applied in magnetism.

The magnetic field is circular because electric fields travel in straight lines radially from the charges, as well as, the changes in the electric field. Therefore the infinitesimal units, which encode the changes in the electric field due to charge movements, propagate radially in the space interacting with current elements. The interaction between a current element and infinitesimal units produces a perpendicular force on that element as described in equation (9) [10]. This force always lies in the plane defined by the source current element and the position vector. This force is computed using the cross product between the vectors, therefore, the virtual field vector generating this force, which is computed by removing the destination current element part from equation (9), is always perpendicular to the plane formed by the source element and position vector as defined in equation (11).

$$\overrightarrow{dB_1}(\overrightarrow{r}) = \frac{\mu}{4\pi}\,\frac{I_1}{|\overrightarrow{r}|^2}\,dl\,(\overrightarrow{a_1} \times \overrightarrow{a_r}). \tag{11}$$

where $\overrightarrow{dB_1}(\overrightarrow{r})$ is the virtual field line vector generating the observed magnetic force produced by current element $\overrightarrow{dI_1}$. Rotating this plane around its center, i.e., source element, in a full circle rotates the field vector without changing its amplitude, refer to figure (10). The traces of this field vector in the space during this rotation forms a closed circle. Mathematically, the magnetic field produced by the infinitesimal current element $\overrightarrow{dI_1}$ is proved to be forming closed circles by showing that the magnetic field has no divergence, i.e., $\nabla \cdot \overrightarrow{dB_1}(\overrightarrow{r}) = 0$, where $\nabla\cdot$ is the divergence symbol. Classically, the proof starts from Biot-Savart law, then uses the fact that the curl of a gradient is equal to zero to show

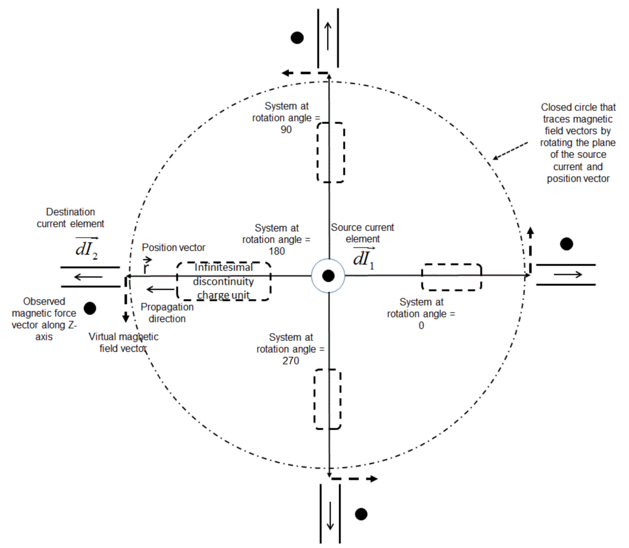

FIGURE 10. Shows the closed circle formed by the virtual field lines generating the magnetic force due to the existence of the source current element $\overrightarrow{dl_1}$. The direction of the field line is shown at four rotation angles of the plane formed by $\overrightarrow{dl_1}$ and the position vector $\vec{r}$ around the source element. Notice that the source element is along the Z-axis. This circle does not have a start or end, which is consistent with the prediction of Maxwell's equations, i.e., static magnetic field lines form closed loops always.

that $\nabla \cdot \overrightarrow{dB_1}(\vec{r}) = 0$, the detailed proof is provided in [1], [42]. In addition to that, this theory provides another way to prove this property that is based on the electric field origin of the magnetic field. The electric field forming the magnetic field is completely inside the plane formed by $\vec{a_1}$ and $\vec{a_r}$ and independent of the direction defined by $\vec{a_1} \times \vec{a_r}$, refer to [10] for the detailed proof, details have been omitted to avoid redundancy and they are too long to be placed in this paper. This plane is perpendicular to the magnetic field direction defined by $\vec{a_1} \times \vec{a_r}$.

So $\overrightarrow{dE_1}(\vec{r}) \cdot (\vec{a_1} \times \vec{a_r}) = 0$, where $\overrightarrow{dE_1}(\vec{r})$ is the electric field of the discontinuity charges generated by the source current element that are producing the observed magnetic field. The magnetic field is defined as a function of $\overrightarrow{dE_1}(\vec{r})$ as in equation (12).

$$\overrightarrow{dB_1}(\vec{r}) = f(|\overrightarrow{dE_1}(\vec{r})|)(\vec{a_1} \times \vec{a_r}) \tag{12}$$

where f is a scalar function of the magnitude of $\overrightarrow{dE_1}(\vec{r})$. $|\overrightarrow{dE_1}(\vec{r})|$ is the magnitude of $\overrightarrow{dE_1}(\vec{r})$. From now on, the position variable $(\vec{r})$ is removed from $\overrightarrow{dE_1}(\vec{r})$ and $\overrightarrow{dB_1}(\vec{r})$ in equations to simplify the representation, so even if it is not shown, they still operate at $(\vec{r})$. The divergence of the electric field is equal to the charge density divided by the permittivity of space. Therefore, the divergence of the electric field forming the magnetic field is zero, i.e., $\nabla \cdot \overrightarrow{dE_1} = 0$, because the net charge of the discontinuity charges enclosed inside the infinitesimal discontinuity unit is zero, see figure (1 c). This indicates that the divergence of the associated magnetic field is zero, consequently. By applying the divergence operation on the magnetic field as defined in equation (12), equation (13) is obtained.

$$\nabla \cdot \overrightarrow{dB_1} = \nabla \cdot (f(|\overrightarrow{dE_1}|)(\vec{a_1} \times \vec{a_r})) \tag{13}$$

Using the divergence product rule, equation (13) is rewritten as in equation (14).

$$\nabla \cdot \overrightarrow{dB_1} = \nabla f(|\overrightarrow{dE_1}|) \cdot (\vec{a_1} \times \vec{a_r}) + f(|\overrightarrow{dE_1}|)\nabla \cdot (\vec{a_1} \times \vec{a_r}) \tag{14}$$

The first term in equation (14) is equal to zero because $\overrightarrow{dE_1}$ has no component along the direction of the magnetic field, $(\vec{a_1} \times \vec{a_r})$, and independent of it. Therefore, $\nabla f(|\overrightarrow{dE_1}|)$ has no component along $(\vec{a_1} \times \vec{a_r})$, so they are perpendicular to each other, i.e., $\nabla f(|\overrightarrow{dE_1}|) \cdot (\vec{a_1} \times \vec{a_r}) = 0$.

The second term in equation (14) is equal to zero. Using the divergence cross product rule, $\nabla \cdot (\vec{a_1} \times \vec{a_r})$ is rewritten as in equation (15).

$$\nabla \cdot (\vec{a_1} \times \vec{a_r}) = (\nabla \times \vec{a_1}) \cdot \vec{a_r} - \vec{a_1} \cdot (\nabla \times \vec{a_r}) \tag{15}$$

The unit vectors $\vec{a_1}$ and $\vec{a_r}$ have no component along the direction $(\vec{a_1} \times \vec{a_r})$ and they are independent of it. Therefore $(\nabla \times \vec{a_1}) \cdot \vec{a_r}$ and $\vec{a_1} \cdot (\nabla \times \vec{a_r})$ are both evaluated to zero. Then, the divergence of the magnetic field generated by the source infinitesimal element is zero, $\nabla \cdot \overrightarrow{dB_1} = 0$. Hence the magnetic field lines form closed circles.

These circles do not have a start or end, which is consistent with the prediction of Maxwell's equations, i.e., static magnetic field lines form closed loops always. This indicates that monopoles do not exist, because they require to break the magnetic field circle to have a start and an end, i.e., source and sink. This may explain why there is no known experimental or observational evidence that magnetic monopoles exist.

A moving charge produces a magnetic field around it because its movement creates changes in the electric field spreading in the space. These changes create discontinuity charges that interact with current elements to produce the observed magnetic force as described in this theory. Static charges do not create these changes in the electric field, therefore no discontinuity charges are produced. So, no magnetic force is generated.

A charge feels the effect of the magnetic field only when it is moving is explained as follows. When a charge is static, it stays in the same position during dt. So the surrounding discontinuity charges at t_i^- are the opposite of the surrounding ones at t_i^+, refer to figure (11). So the total electric force applied on the charge at t_i is zero as indicated in equation (10). When the charge moves, the surrounding discontinuity charges stay the same at t_i^- and t_i^+ because the charge changes its position during the infinitesimal interval dt at t_i as explained in this theory, refer to figure (9). Hence the observed magnetic force on moving charges.

Regarding how Newton's third law is applied in magnetism, this law has been proved to be satisfied in magnetism using the conservation of momentum explanation [43], [44]

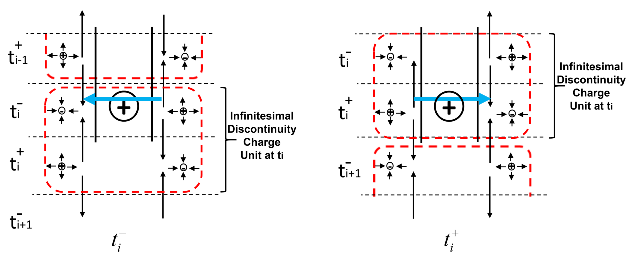

FIGURE 11. Shows the interaction of a positive static charge with a crossing infinitesimal discontinuity charge unit at t_i. Notice that the forces applied on the charge at t_i^- and t_i^+ are opposing each other. So the total force applied on the charge at t_i is zero, so no static magnetic force is observed on static charges.

but this proof does not specify how. This question is answered by this theory as follows. The electric charges of current elements interact with each other through the discontinuity charges. The electric force between a current charge and a discontinuity charge satisfies Newton's third law. The forces exerted on current charges allow the charges to produce either a non-zero or zero net force on the containing infinitesimal current element. The push interaction between the current charges and the containing current element obeys Newton's third law as in the interaction between particles.

The provided analysis in this work is developed for an infinitesimal filament element. The total applied force on a larger filament or larger volume is found by summing the contributions from all the infinitesimal filament elements comprising the larger one.

V. CONCLUSION

This paper presented the first general framework for the theory of the electric origin of the magnetic force that is relativistic invariant and consistent with the electromagnetic theory. In any frame, the observed magnetic force between two direct current elements in that frame is explained as a result of electric interactions between electric charges. The explanation depends on analyzing the electric field spreading in the space due to the moving charges inside current elements. The explanation starts by defining a 3D space with its infinitesimal elements that facilitates tracking electric field changes in the space due to charges moving at different speeds. The spreading electric field in the space contains discontinuity points to indicate the changes in positions of these charges. Applying Gauss's law at these discontinuity points indicates the existence of electric charges, referred to as discontinuity charges. These discontinuity charges interact with the moving charges inside current elements to produce a force that is equivalent in magnitude and direction to the observed magnetic force at these elements. This explanation is proved by deriving the magnetic force law and Biot-Savart law using the basis of electric forces. Further research is required to investigate the nature of the electric force, the electric charge and the effect of its movement in the space, as well as, to extend this theory to address accelerating charges, and to address how it facilitates the derivation of Maxwell's equations for magnetism. This theory helps better understand magnetic force properties and unifies the origin of magnetism and electricity. This work is important to answer the question about "What is Magnetism" and the existence of monopoles, which is one of the top unsolved problems in physics, as well as, it may help engineers in developing new technologies and applications for magnetism.

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