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A Study of Quadratic Forms for One of the High-Dimensional Diophantine Equation $\alpha({p_1}^3+{q_1}^3+{r_1}^3)(X^m+Y^m)=(C^2-D^2)(Z^2-W^2)P^\beta$ With $\alpha>0,\beta>0,m>0$ and $X<Y<W<Z$

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ABSTRACT:
The approach underscores an interdisciplinary bridge between classical Diophantine analysis and embedded-system optimization, highlighting how number-theoretic constraints can be engineered into the very fabric of cryptographic hardware. In this paper we focus on a given higher-degree Diophantine equation of the form

$$\alpha({p_1}^3+{q_1}^3+{r_1}^3)(X^m+Y^m)=(C^2-D^2)(Z^2-W^2)P^\beta$$

With $\alpha>0,\beta>0,m>0$ and $X<Y<W<Z.$

where

$$\{p_1,q_1,r_1\}=\left\{\begin{array}{c}(-6,-8,9),(9,10,-12),(64,94,-103),(-71,-138,144),\\(73,144,-150),(-135,-138,172),\\(135,235,-249)\\(334,438,-495),(-372,-426,505),(-426,-486,577),(-242,-720,729)\end{array}\right\}$$

With ${p_1}^3+{q_1}^3+{r_1}^3=1$

Having integer design of solutions **for** $\beta>2$ is parameterized by positive integers k, m and n, with variables defined as:

$$x=k^n,y=k^{n+1},z=k^{n+3},w=k^{n+2},p=k^n,$$

$$\alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2,\quad\left\{\begin{array}{ll}C=\left(\left(\frac{1+k^m}{2}\right)^2+1\right)n,D=\left(\left(\frac{1+k^m}{2}\right)^2-1\right)n, & if\ 1+k^m\ is\ even\\C=\left(\frac{(1+k^m)^2+1}{2}\right)n,\quad D=\left(\frac{(1+k^m)^2-1}{2}\right)n, & if\ 1+k^m\ is\ odd\end{array}\right\}.$$

In this paper also focused on Diophantine-style constraints can be useful if:

- They are embedded as regularizes or hard constraints in a larger continuous optimization (e.g., integer-lattice constraints via rounding or projection), rather than solved exactly.
- exploit lattice-reduction techniques (LLL, etc.) to preprocess or approximate the integer structure, then solve a relaxed problem online.

In short, Diophantine methods are best treated as design-time tools (for constructing hard problems, lattices, or integer constraints) rather than as the primary engine for real-time optimization loops.

KEYWORDS: Diophantine Equation, exponential, Pythagorean triplet, Integer design.

I. INTRODUCTION

Cryptography on embedded devices: Second-degree (quadratic) Diophantine systems have been used to encode message-transmission algorithms in lightweight cryptographic protocols suitable for microcontrollers and IoT nodes. In such schemes, the encryption and decryption rules are derived from integer solutions of quadratic

Diophantine equations or small systems thereof, so that only a legitimate user who knows the underlying Diophantine structure can efficiently recover the plaintext.
Parameterized Diophantine solvers: Recent work explicitly bridges exponential and high-degree Diophantine equations—including quadratic and quintic-type forms—to embedded-system tasks such as:

- Residue-number-system (RNS) encoding using Pythagorean-like tuples, where parameterized integer solutions of equations such as a2+b2=c2$a2+b2=c2$ are used to construct RNS bases or redundancy schemes tailored to low-power arithmetic units.

- High-Dimensional-Curve Cryptography (HCC) key-generation constraints, where Diophantine conditions on curve parameters (e.g., generalized Fermat-type or higher-degree forms) are imposed to ensure desirable arithmetic properties or resistance to certain attacks.

- Pole-placement and control-law parameterization, where Diophantine solutions of characteristic-equation constraints yield discrete-time feedback gains compatible with fixed-point, resource-constrained controllers.

Concrete embedded-system angles

- Arithmetic units: Implementing solvers for small-scale quadratic Diophantine equations (e.g., Pell-type equations or norm-form equations) in FPGA or ASIC blocks can accelerate cryptographic or control computations on resource-constrained platforms. These blocks often exploit parameterized families of solutions indexed by integers k,m,n, so that key-related or control-related parameters are generated on-chip without full-scale lattice reduction.

- Security primitives: Mapping quintic or higher-degree Diophantine relations into hard-to-invert functions gives candidate building blocks for lightweight ciphers or hash-like constructions tailored to embedded environments, especially when combined with RNS or lattice-based encodings.

Diophantine equations—polynomial equations with integer solutions—are a central topic in number theory. Among their many variants, exponential Diophantine equations involve terms where variables appear as exponents, and finding integer solutions to such equations is notably complex. This complexity has implications in mathematics, cryptography, and several scientific fields, motivating the design of parameterized families and approximate solvers that can be deployed in real-time embedded systems. Pythagorean triples from Diophantine solutions support Residue Number System (RNS) encoding for efficient arithmetic in embedded control, linking to triples generation pipelines.

The equation $\boldsymbol{\alpha}(\boldsymbol{p_1}^3+\boldsymbol{q_1}^3+\boldsymbol{r_1}^3)(\boldsymbol{X^m}+\boldsymbol{Y^m})=(\boldsymbol{C^2}-\boldsymbol{D^2})(\boldsymbol{Z^2}-\boldsymbol{W^2})\boldsymbol{P^\beta}$
With $\boldsymbol{\alpha>0,\beta>0,m>0\ and\ X<Y<W<Z}$ **.** generalizes Fermat-like forms for cryptographic primitives or curve parameters, though specific instances tie to triple-based HCC. These unify cryptography, allocation, and control in resource-limited settings.
For microcontroller Diophantine solvers like LLL-based methods excel in real-time control, outperforming floats in integer tasks despite hardware FPUs. Progressive variants cut time for HCC-like reductions while fitting memory limits.
This paper focused on a study to find integer design of solutions Diophantine Equation

$$\boldsymbol{\alpha}(\boldsymbol{p_1}^3+\boldsymbol{q_1}^3+\boldsymbol{r_1}^3)(\boldsymbol{X^m}+\boldsymbol{Y^m})=(\boldsymbol{C^2}-\boldsymbol{D^2})(\boldsymbol{Z^2}-\boldsymbol{W^2})\boldsymbol{P^\beta}$$

With $\boldsymbol{\alpha>0,\beta>0,m>0\ and\ X<Y<W<Z}$ **.**

Diophantine equations of higher degrees, play a meaningful role in generating special elliptic curves that are crucial for cryptography and secure communications.

II. RESULTS & DISCUSSIONS

In this paper, focused to find the general exponential integer solution of the general exponential integer solution of $\boldsymbol{\alpha}(\boldsymbol{p_1}^3+\boldsymbol{q_1}^3+\boldsymbol{r_1}^3)(\boldsymbol{X^m}+\boldsymbol{Y^m})=(\boldsymbol{C^2}-\boldsymbol{D^2})(\boldsymbol{Z^2}-\boldsymbol{W^2})\boldsymbol{P^\beta}$
With $\boldsymbol{\alpha>0,\beta>0,m>0}$ **is derived from fixed value of** $\boldsymbol{\beta}$**.**
Proportion 1: A Study on exponential integer solution of above Diophantine Equation at
$\boldsymbol{\beta=1}$ **is** $\boldsymbol{\alpha}(\boldsymbol{p_1}^3+\boldsymbol{q_1}^3+\boldsymbol{r_1}^3)(\boldsymbol{X^m}+\boldsymbol{Y^m})=(\boldsymbol{C^2}-\boldsymbol{D^2})(\boldsymbol{Z^2}-\boldsymbol{W^2})\boldsymbol{P}$

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Explanation: Consider

$$\{p_1, q_1, r_1\} = \left\{ \begin{array}{c} (-6,-8,9),(9,10,-12),(64,94,-103),(-71,-138,144), \\ (73,144,-150),(-135,-138,172), \\ (135,235,-249) \\ (334,438,-495),(-372,-426,505),(-426,-486,577),(-242,-720,729) \end{array} \right\}$$

With $\boldsymbol{p_1}^3 + \boldsymbol{q_1}^3 + \boldsymbol{r_1}^3 = \mathbf{1}$.

Let x = $k^n, y = k^{n+1}, z = k^{n+3}, w = k^{n+2}, p = k^n$,

Consider $\alpha(X^m + Y^m) = \alpha k^{nm}(1 + k^m)$.

Again consider $(\boldsymbol{C^2} - \boldsymbol{D^2})(\boldsymbol{Z^2} - \boldsymbol{W^2})\boldsymbol{P^\beta} = (C^2 - D^2)k^{(\boldsymbol{\beta}+2)n}(k^6 - k^4)$

It follows that $\boldsymbol{\alpha}(\boldsymbol{X^4} + \boldsymbol{Y^4}) = (\boldsymbol{C^2} - \boldsymbol{D^2})(\boldsymbol{Z^2} - \boldsymbol{W^2})\boldsymbol{P^\beta}$ implies that

$\alpha k^{mn}(1 + k^m) = (C^2 - D^2)k^{(\boldsymbol{\beta}+2)n}(k^6 - k^4)$ implies

$\alpha(1 + k^m) = k^{(\boldsymbol{\beta}+2-m)n}(C^2 - D^2)(k^6 - k^4)$.

Solve for α, whenever $(1 + k^m, D, C)$ is a Pythagorean Triplet.

From the References [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12] there is so many methods to generate Pythagorean triplet,

$$S_1 = \left\{(x, y, z): \frac{z}{y} = 1 + \frac{2}{x^2 - 1} \text{ if } x \text{ is an odd prime number or its power}\right\}$$

$$S_2 = \left\{(x, y, z): \frac{z}{y} = 1 + \frac{2}{\left(\frac{x}{(2p-1)^2}\right)^2 - 1} \text{ if } x \text{ is an odd composite or its Power, for some } p = 1,2,3\ldots\right\}$$

$$S_3 = \left\{(x, y, z): \frac{z}{y} = 1 + \frac{2}{\left(\frac{x}{2}\right)^2 - 1} \quad if\ x \text{ is geometric power of } 2\right\}$$

$$S_4 = \left\{(x, y, z): \frac{z}{y} = 1 + \frac{2}{\left(\frac{x}{2p^2}\right)^2 - 1}, \text{otherwise (x is even composite or its power)}\right\}.$$

now I chosen one of the technique of

if r is an even number, then (r, $\left(\frac{r}{2}\right)^2 - 1, \left(\frac{r}{2}\right)^2 + 1$) is a Pythagorean triplet.

If r is an odd number, then (r, $\frac{r^2-1}{2}, \frac{r^2+1}{2}$) is a Pythagorean triplet.

It implies that $(1 + k^m, D, C)$ becomes a Pythagorean Triplet depending on *whether* $1 + k^m$ is odd or even.

Case 1: **If $\mathbf{1} + \boldsymbol{k^m}$ is even**, then ($1 + k^m, \left(\frac{1+k^m}{2}\right)^2 - 1, \left(\frac{1+k^m}{2}\right)^2 + 1$) is a Pythagorean triplet.

It follows that $\alpha(1 + k^m) = k^{(\boldsymbol{\beta}+2-m)n}(C^2 - D^2)(k^6 - k^4)$ and solve for α,

whenever $(1 + k^m, D, C)$ becomes a Pythagorean Triplet with $C = \left(\left(\frac{1+k^m}{2}\right)^2 + 1\right)n$,

$D = \left(\left(\frac{1+k^m}{2}\right)^2 - 1\right)n \ and \ C^2 - D^2 = (1 + k^m)^2 n^2$ and hence

$\alpha = k^{(\boldsymbol{\beta}+2-m)n}(1 + k^m)(k^6 - k^4)n^2$.

Hence, **we obtain** $(X^m + Y^m) = (C^2 - D^2)(Z^2 - W^2)P$ **having integer design of solution is**

x $= k^n, y = k^{n+1}, z = k^{n+3}, w = k^{n+2}, p = k^{2n},$

$C = \left(\left(\frac{1+k^m}{2}\right)^2 + 1\right)n,\ D = \left(\left(\frac{1+k^m}{2}\right)^2 - 1\right)n, \alpha = k^{(\beta+2-m)n}(1+k^m)(k^6 - k^4)n^2.$

Verification:

Consider **LHS**

$\alpha(X^m + Y^m) = k^{(\beta+2-m)n}(1+k^m)(k^6 - k^4)n^2(k^{mn} + k^{mn+m})$

$= k^{\beta+2}(k^6 - k^4)(1+k^m)^2 n^2$

Consider RHS

$T^2(C^2 - D^2)(Z^2 - W^2)P = (3(4)^n)^2(1+k^m)^2 n^2 (k^{2n+6} - k^{2n+4})k^{\beta n}$

$= k^{\beta+2}(k^6 - k^4)(1+k^m)^2 n^2.$

Hence LHS $= RHS.$

Case 2: If $1 + k^m$ **is odd**, then $\left(1 + k^m, \frac{(1+k^m)^2-1}{2}, \frac{(1+k^m)^2+1}{2}\right)$ is a Pythagorean triplet. It follows that $\alpha(1+k^m) = k^{(\beta+2-m)n}(C^2 - D^2)(k^6 - k^4)$ and solves for α, whenever

$(1+k^m, D, C)$ becomes a Pythagorean Triplet with $C = \left(\frac{(1+k^m)^2+1}{2}\right)n,\ D = \left(\frac{(1+k^m)^2-1}{2}\right)n.$

Hence $C^2 - D^2 = (1+k^m)^2 n^2$ and hence $\alpha = k^{(\beta+2-m)n}(C^2 - D^2)(k^6 - k^4).$

Hence, $(X^m + Y^m) = (C^2 - D^2)(Z^2 - W^2)P$ **having integer design of solution is**

x $= k^n, y = k^{n+1}, z = k^{n+3}, w = k^{n+2}, p = k^{2n},$

$C = \left(\frac{(1+k^m)^2+1}{2}\right)n,\ D = \left(\frac{(1+k^m)^2-1}{2}\right)n,\ \alpha = k^{(\beta+2-m)n}(1+k^m)(k^6 - k^4)n^2.$

Verification: Consider **LHS**

$\alpha(X^m + Y^m)(5U^2 + V^2) = k^{(\beta+2-m)n}(1+k^m)(k^6 - k^4)n^2(k^{mn} + k^{mn+m})$

$= k^{\beta+2}(k^6 - k^4)(1+k^m)^2 n^2$

Consider RHS

$$(C^2 - D^2)(Z^2 - W^2)P = (1+k^m)^2 n^2 (k^{2n+6} - k^{2n+4})k^{\beta}$$

$= k^{\beta+2}(k^6 - k^4)(1+k^m)^2 n^2.$

Hence LHS $= RHS.$

III. ALGORITHM FOR HIGHER DIMENSIONAL CURVE CRYPTOGRAPHY

From the References [13],[14],[15],[16],[17],[18],[19],[20],[21],[22],[23],[24]

(I) Ep (X, Y, Z, W, U, V, T):

$$(p_1{}^3 + q_1{}^3 + r_1{}^3)\ (X^m + Y^m) = (C^2 - D^2)(Z^2 - W^2)P^{\beta}$$

is the equation for an elliptic curve, where Ep is an higher degree curve defined over the finite field Ep for **x** $= k^n, y = k^{n+1}, z = k^{n+3}, w = k^{n+2}, p = k^n,$

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$$\{p_1, q_1, r_1\} = \left\{ \begin{array}{c} (-6,-8,9),(9,10,-12),(64,94,-103),(-71,-138,144), \\ (73,144,-150),(-135,-138,172), \\ (135,235,-249) \\ (334,438,-495),(-372,-426,505),(-426,-486,577),(-242,-720,729) \end{array} \right\}$$

(II) **Key Generating**: The message will be encrypted by the sender using the recipient's public key and the recipient will use his private key to decrypt it.

(i) Let "M" be the point on the higher degree curve.

(ii) Select "M" as the point fromEp (X, Y,).

(iii) Choose generator point $\boldsymbol{\beta}$ in Ep (X, Y, Z, W).

(iv) Select a private key n from the interval $1 \le n \le p-1$ and utilize it to compute $\boldsymbol{\beta}$ the public key.

(v) Choose a number M that falls LHS of higher degree curve.

$M = (\boldsymbol{X^m} + \boldsymbol{Y^m})$.

(III) **Encryption**:

Let $\boldsymbol{\alpha}$ cipher texts that will be generated. $\boldsymbol{\alpha} = k^{(\beta+2-m)n}(\mathbf{1} + \boldsymbol{k^m})(\boldsymbol{k^6} - \boldsymbol{k^4})\boldsymbol{n^2}$

(IV) **Decryption**:

The original point that we have sent, point "M", needs to be decrypted using the formula

M= $(\boldsymbol{C^2} - \boldsymbol{D^2})(\boldsymbol{Z^2} - \boldsymbol{W^2})\boldsymbol{P}$, as it was sent to the recipient.

E.g. 1: Suppose k = 2, m = 4, $\boldsymbol{\beta} = \mathbf{1}$ then $1 + k^m = 1 + k^4$ = 17, is odd; Having an integer design of solution is

$x = 2^n, y = 2^{n+1}, z = 2^{n+3}, w = 2^{n+2}, p = 2^{2n}$,

$C = \left(\frac{(1+2^4)^2+1}{2})\right) n = 145n,\ D = \left(\frac{(1+2^4)^2-1}{2}\right) = 144n$

$C^2 - D^2 = (1+2^4)^2 n^2,\ \alpha = (1+2^4)(2^6 - 2^4)n^2.$

Suppose n = 1; then x = 2, $y = 4, z = 16, w = 8, p = 4$,

$C = \left(\frac{(1+2^4)^2+1}{2})\right) = 145,\ D = \left(\frac{(1+2^4)^2-1}{2}\right) = 144$

$C^2 - D^2 = (1+2^4)^2 = 289,\ \alpha = (1+2^4)(2^6 - 2^4) = 816.$

Consider **LHS=** $\boldsymbol{\alpha}(\boldsymbol{X^4} + \boldsymbol{Y^4})$ **=816**$(\mathbf{2^4} + \mathbf{4^4}) = \mathbf{221952}$.

RHS = $(\boldsymbol{C^2} - \boldsymbol{D^2})(\boldsymbol{Z^2} - \boldsymbol{W^2})\boldsymbol{P} = \mathbf{289} * (\mathbf{16^2} - \mathbf{8^2}) * \mathbf{4} = \mathbf{221952}$.

E.g. 2: Suppose k = 3, m = 4, $\boldsymbol{\beta} = \mathbf{1}$ then $1 + k^4$ = 82, is even; Having an integer design of solution is

$x = 3^n, y = 3^{n+1}, z = 3^{n+3}, w = 3^{n+2}, p = 3^{2n}$,

$C = \left(\left(\frac{1+3^4}{2}\right)^2 + 1\right) n = 1681n,\ D = \left(\left(\frac{1+3^4}{2}\right)^2 - 1\right) n = 1600n$

$C^2 - D^2 = (1+3^4)^2 n^2 = 6724n,\ \alpha = (1+3^4)(3^6 - 3^4)n^2 = 53136n^2.$

Suppose n = 1; then x = 3, $y = 9, z = 81, w = 27, p = 9, C^2 - D^2 = 6724,\ \alpha = 53136$

Consider **LHS=** $\boldsymbol{\alpha}(\boldsymbol{X^4} + \boldsymbol{Y^4})$ **=53136**$* (\mathbf{3^4} + \mathbf{9^4}) = \mathbf{352929312}$.

RHS = $(\boldsymbol{C^2} - \boldsymbol{D^2})(\boldsymbol{Z^2} - \boldsymbol{W^2})\boldsymbol{P} = \mathbf{6724} * (\mathbf{81^2} - \mathbf{27^2}) * \mathbf{9} = \mathbf{352929312}$

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V. CONCLUSION

In summary, this research paper contributes to the ongoing efforts to explore novel mathematical constructs in the design of secure and efficient cryptographic systems. By harnessing the properties of Diophantine triples and special polynomial sequences, it's possible to develop elliptic curves that offer robust security features for modern cryptographic applications. It distinguishes from classical Diophantine studies by highlighting exponential forms, high dimensionality, and applications like elliptic curve cryptography primitives, Fermat-like generalizations, and integer-based real-time solvers outperforming FPUs. In this paper, focused given Diophantine equation with more than 8 unknowns $\boldsymbol{\alpha(p_1{}^3+q_1{}^3+r_1{}^3)(X^m+Y^m)=(C^2-D^2)(Z^2-W^2)P^\beta}$

With $\boldsymbol{\alpha>0,\beta>0,m>0 \text{ and } X<Y<W<Z}$

Having integer design of solutions **for** $\boldsymbol{\beta>2}$ is parameterized by positive integers k, m and n, with variables defined as: $\mathbf{x}=\boldsymbol{k^n, y=k^{n+1}, z=k^{n+3}, w=k^{n+2}, p=k^n}$, $\boldsymbol{\alpha=k^{(\beta+2-m)n}(1+k^m)(k^6-k^4)n^2}$,

$$\left\{\begin{array}{c} \boldsymbol{C=\left(\left(\frac{1+k^m}{2}\right)^2+1\right)n, D=\left(\left(\frac{1+k^m}{2}\right)^2-1\right)n, \quad if\ 1+k^m\ is\ even} \\ \boldsymbol{C=\left(\frac{(1+k^m)^2+1}{2}\right)n, D=\left(\frac{(1+k^m)^2-1}{2}\right)n, \quad if\ 1+k^m\ is\ odd} \end{array}\right\} \text{ and}$$

$$\{p_1,q_1,r_1\} = \left\{\begin{array}{c} (-6,-8,9),(9,10,-12),(64,94,-103),(-71,-138,144), \\ (73,144,-150),(-135,-138,172), \\ (135,235,-249) \\ (334,438,-495),(-372,-426,505),(-426,-486,577),(-242,-720,729) \end{array}\right\}$$

With $\boldsymbol{p_1{}^3+q_1{}^3+r_1{}^3=1}$

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