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Development of Graphical User Interface (GUI) for Numerical Integration with Application

Nurul Farrah Natasha Azraime[1], Mohd Rashid Admon[1,*]

[1] Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

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ABSTRACT

Numerical integration is a key technique for approximating definite integrals, especially when analytical solutions are difficult or impossible to obtain. Although various numerical methods exist, most tools lack an intuitive interface for comparing their efficiency and accuracy. This study develops a MATLAB-based Graphical User Interface that implements five selected integration methods which are Gaussian Quadrature, Simpson's 1/3 Rule, Simpson's 3/8 Rule, the Trapezoidal Rule, and the Midpoint Rule. The Graphical User Interface, designed using MATLAB Application Designer, enables users to input functions, define integration limits, step sizes, and subintervals, and provides tables, graphs, and error analyses for result visualization. Comparative evaluations, including case studies and applications in fluid dynamics, option pricing, and medical dosage, demonstrate that Gaussian Quadrature consistently delivers the highest accuracy, followed by Simpson's 1/3 Rule and Simpson's 3/8 Rule, while the Midpoint and Trapezoidal Rules yield larger errors. The proposed tool facilitates clear performance comparison and supports informed method selection, making it well-suited as an educational platform that enhances accessibility and understanding of numerical integration methods.

1. Introduction

In domains such as engineering, physics, and finance, numerical integration is crucial for resolving definite integrals when analytical solutions are impractical. Approximation techniques are necessary because many real-world situations contain complex or empirical functions that are challenging to integrate analytically. Effective solutions are obtained by using numerical approaches such the Trapezoidal Rule, Simpson's Rules, Midpoint Rule, and Gauss Quadrature, which divide the issue into manageable calculations. However current tools frequently lack an easy-to-use interface that makes comparing and using these techniques simple.

This study fills that gap by creating a Graphical User Interface (GUI) based on MATLAB that combines five common techniques including Gauss Quadrature Rule, Midpoint Rule, Simpson's 1/3 Rule, Simpson's 3/8 Rule, and Trapezoidal Rule. Users may specify step sizes or subintervals, define

* *Corresponding author.*
E-mail address: m.rashid@utm.my

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integration restrictions, and input functions using the Graphical User Interface. They can evaluate the results, related errors, and visual comparisons between all techniques. This application makes numerical integration more accurate and accessible, which benefits professionals, educators, and students alike.

The Graphical User Interface facilitates real-world problem solving, fosters greater comprehension, and makes difficult mathematical calculations easier by providing an intuitive platform and automated analysis. Additionally, it serves as a teaching tool, assisting users in gaining an understanding of the advantages and disadvantages of various numerical techniques in a practical setting.

1.1 Numerical Integration
1.1.1 Trapezoidal rule

Trapezoidal Rule sums up the areas of trapezoids beneath a curve to approximate the integral. Press *et al.,* [1] state that the Trapezoidal Rule minimises error and works effectively when the integrand is smooth and the interval is precisely divided. However, the Trapezoidal Rule has significant drawbacks, particularly with regard to accuracy, even if it is computationally straightforward. Additionally, in computer engineering, Ali and Abbas [2] state that trapezoidal method was used to solve fractional differential equations with different numerical techniques by checking the accuracy and stability in a high-resolution digital system.

Trapezoidal Rule is defined as Eq. (1):

$$\int_a^b f(x)dx \approx \frac{h}{2}\,[f(a)+f(b)], \qquad h=b-a \tag{1}$$

where:
$h =$ step size of each interval.
a = upper limit of integration.
b = lower limit of integration.

1.1.2 Simpson’s 1/3 rule

Simpson's 1/3 Rule's fundamental concept is to approximate the function using quadratic polynomials rather than linear polynomials, which enhances the Trapezoidal Rule. This improves its accuracy for continuous and smooth functions. Simpson's 1/3 Rule formula is very useful for many real-world applications in the physical sciences and engineering as it is made to yield precise answers for polynomial functions of degree three or less. According to Burden and Faires [3], this improved accuracy results from the method's ability to address the curvature of the integrated function.

Simpson’s 1/3 Rule is defined as Eq. (2):

$$\int_a^b f(x)dx \approx \frac{h}{3}\,[f(a)+4f(a+h)+f(b)],\; h = \frac{b-a}{2} \tag{2}$$

where:
$h =$ step size of each interval.

a = upper limit of integration.
b = lower limit of integration.

1.1.3 Simpson's 3/8 rule

Simpson's 3/8 Rule is a numerical integration method that enhances the accuracy of definite integral approximations by employing cubic polynomials. The core idea behind the 3/8 Rule is to approximate the area under a curve by dividing the interval of integration into segments consisting of three equal parts. In practical applications, Simpson's 3/8 Rule is widely used in fields such as engineering, physics, and finance, where the need to compute integrals from real-world data is common.

Simpson's 3/8 Rule is defined as Eq. (3):

$$\int_a^b f(x)dx \approx \frac{3}{8}h[f(a)+3f(a+h)+3f(a+2h)+f(b)]\,, h = \frac{b-a}{3} \tag{3}$$

where:
$h =$ step size of each interval.
a = upper limit of integration.
b = lower limit of integration.

1.1.4 Midpoint rule

Midpoint Rule approximates the integral of a function by calculating the value of the function at the midpoint of each subinterval, and then summing these values to estimate the total area under the curve. Early developments in numerical integration focused on partitioning the area under a curve into simple shapes, such as rectangles, for easier computation. According to Subramaniam and Gilat [4], Midpoint Rule is an improvement over the naive rectangle method . Midpoint Rule does have limitations. For functions with sharp corners or rapid changes, the Midpoint Rule's approximation can still be inaccurate, especially with fewer subintervals that state by Kharab *et al.,* [5]. For example, Stroud [6] state that Midpoint Rule has been employed in computing work and energy in mechanical systems.

Midpoint Rule is defined as Eq. (4):

$$\int_a^b f(x)dx \approx h\sum_{i=1}^{n} f(x_i) \tag{4}$$

where:
$h =$ step size of each interval.
a = upper limit of integration.
b = lower limit of integration.

1.1.5 Gauss quadrature rule

Gauss Quadrature Rule approximates the integral of a function by evaluating the function at specific points called nodes within each subinterval and weighting these values appropriately. Gaussian Quadrature is particularly useful when high accuracy is required, especially for functions that can be well-approximated by polynomials. Gaussian Quadrature is widely used in various scientific, engineering, and computational fields. In physics, Gautschi and Walter state that it is employed in solving problems in quantum mechanics, electromagnetism, and fluid dynamics, where integrals often appear in differential equations or energy calculations [7]. In computational finance, state by Wilmott *et al.,* Gaussian Quadrature is applied to calculate areas under probability density functions, cumulative distribution functions, and pricing options [8].

Gauss Quadrature Rule is defined as Eq. (5):

$$\int_a^b f(x)dx \approx h\sum_{i=1}^{n} f(x_i) \tag{5}$$

where:
$h =$ step size of each interval.
a $=$ upper limit of integration.
b $=$ lower limit of integration.

1.2 Numerical Integration in Real World Applications

Computational fluid dynamics (CFD) relies on numerical methods to solve Navier-Stokes equations, which describe the movement of fluids. These equations are integral to applications ranging from aerospace engineering such as designing aircraft wings to predicting weather patterns and ocean currents. According to Ferziger *et al.,* numerical integration enables the discretization of complex fluid behaviors over computational grids, making it possible to model turbulence and optimize designs [9].

In finance, numerical integration underpins the modelling of complex financial systems. Monte Carlo integration, in particular, is essential for pricing derivatives, such as options, by simulating a wide range of possible outcomes. Risk management also employs numerical methods to evaluate high-dimensional integrals associated with portfolio optimization and asset pricing. Based on Hull and Glasserman, these techniques allow financial analysts to account for uncertainty and variability, improving decision-making in volatile markets [10,11].

In medicine, numerical integration is critical for determining appropriate drug dosages. Pharmacokinetics, the study of how drugs are absorbed, distributed, metabolized, and excreted by the body, often involves solving integrals of concentration-time curves. Numerical methods allow for precise calculation of areas under curves (AUC), which are used to optimize dosage regimens. This ensures therapeutic efficacy while minimizing adverse effects. Other than that, Lötstedt state that numerical integration is implemented in the simulation of the mechanical behaviour of biological cells [12].

1.3 Existed GUI Numerical Integration Calculator

There is various numerical integration calculator that available on website. For instance, AtoZmath.com that developed by Piyush N Shah in 2000 [13] are the oldest numerical integration calculator that have been found in website. The calculator offers only the Trapezoidal Rule and Simpson's Rule, making it less useful for users who wish to compare different methods or those who require multiple methods for their calculations. The intuitive design is not user-friendly, making it difficult for users to navigate and use effectively. Otherwise, there is another beneficial numerical integration calculator called Simpson's Rule Calculator, developed by Paul in 2020 [14]. As its name, the calculator only provides a Simpson's rule method which less beneficial compared to others calculator. On top of that, another numerical integration calculator called "PlanetCalc" that have been developed by Anton on 2021 [15] that provides customizable parameters, error estimation and visual presentation that serves as a valuable learning resource for understanding numerical integration concepts. The calculator encounters some interval limitations which the precision of the approximation can be influenced by the number of intervals specified.

2. Methodology

2.1 GUI Development Using MATLAB

Graphical User Interface (GUI) was created using MATLAB App Designer, providing an interactive environment for users to enter inputs and view results. The interface includes:

- Text boxes for entering the function to be integrated.
- Input fields for lower and upper limits of integration.
- Option to define step size or number of subintervals.
- Drop Down boxes to select which integration methods to use.
- Tabs for displaying numerical results, tables, graphs, and errors.

2.2 Numerical Integration Implementation

Each integration method is implemented based on its respective mathematical formulation as described in the literature review. The code accepts the input function and parameters, then computes the approximate value of the definite integral using the selected methods.

- Trapezoidal Rule: Utilizes linear interpolation between each subinterval.
- Simpson's 1/3 and Simpson's 3/8 Rules**:** Apply quadratic and cubic polynomial fitting, respectively.
- Midpoint Rule: Evaluates function at subinterval centers.
- Gauss Quadrature: Applies weighted nodes for high precision.

2.3 Error Calculation and Comparison

The accuracy of each method is calculated by using its error.
Error formula is defined as equation (6):

$$Absolute\ Error = |\ Exact\ Value - Approximated\ Value| \qquad (6)$$

3. Results
3.1. Numerical Integration Calculator (NIC) Interface

The numerical integration calculator within the MATLAB application was carefully implemented to allow users to input functions, integration limits, and step sizes, number of sub interval streamlining the process of calculating definite integrals. The result of Numerical Integration Calculator is displayed in Figure 1.

Based on Figure 1, it begins with user inputs for the function, upper and lower integration limits, step size or number of subintervals. The calculator then computes the exact solution of the given integral, which serves as a reference for error comparison. After obtaining the results, the calculator calculates the error for each approximation by comparing the results to the exact solution. Finally, it generates a table and a graph to show the relationship between the step size and the error for each method.

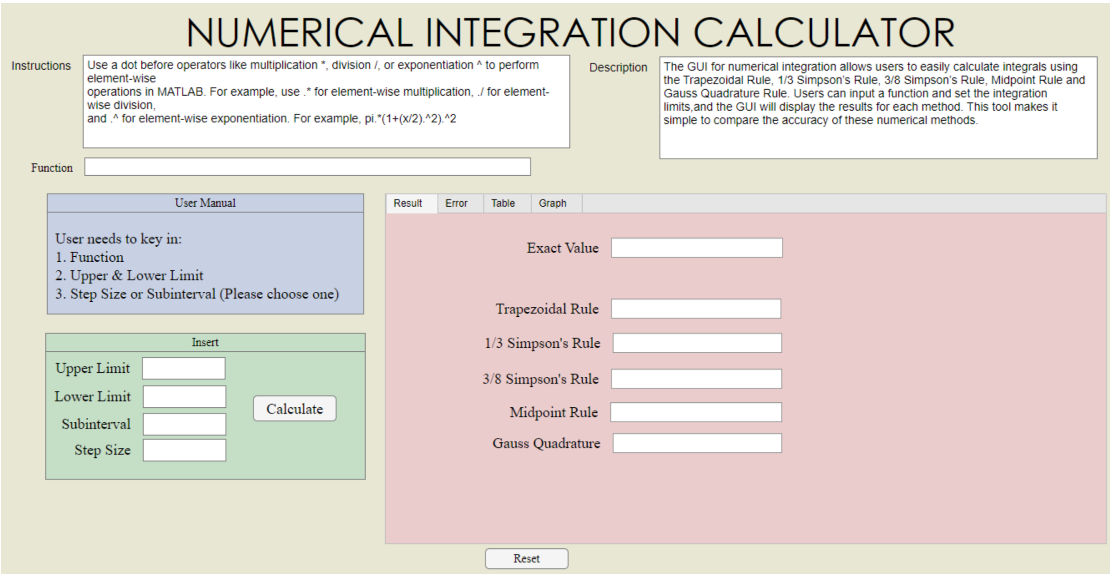

Fig. 1. Numerical integration calculator interface

3.1 Comparative Analysis of Numerical Integration Methods
3.1.1 Case 1 (Che Rahim Che The, 2010)

$$\int_0^1 \frac{2x+1}{\sqrt{4-x^2}}\,dx \tag{7}$$

Exact value of Eq. (7) is 1.0595.

Table 1 and Table 2 shows the numerical analysis of Case 1 is solved by using Trapezoidal rule, Simpson's 1/3 rule, Simpson's 3/8 rule, Midpoint Rule and Gauss Quadrature Rule. Based on Table 1 and Table 2, the results show that Gauss Quadrature gives the most accurate answers, with the smallest error, even when the number of subintervals is low. This method provides highly accurate results because of its use of optimized points and weights. Simpson's 1/3 Rule also gives very good results, with errors that are slightly higher than Gauss Quadrature, but still much smaller than the other methods. Simpson's 3/8 Rule performs slightly less accurately than Simpson's 1/3 Rule, but better than the Trapezoidal and Midpoint Rules. Trapezoidal Rule, although simple to use, shows larger errors and is less accurate overall. Midpoint Rule is slightly more accurate than the Trapezoidal Rule, but still not as reliable as Simpson's 1/3, 3/8 or Gauss Quadrature methods.

Table 1
Result of numerical integration method for Eq. (7) by using numerical integration calculator

Step Sizes	Trapezoidal Rule	Simpson's 1/3 Rule	Simpson's 3/8 Rule	Midpoint Rule	Gauss Quadrature Rule
$\frac{1}{30}$	1.0595649	1.0594972	1.0594972	1.0594633	1.0594972
$\frac{1}{24}$	1.0596031	1.0594972	1.0594973	1.0594442	1.0594972
$\frac{1}{18}$	1.0596854	1.0594974	1.0594977	1.0594031	1.0594972
$\frac{1}{12}$	1.0599205	1.0594983	1.0594997	1.0592856	1.0594971
$\frac{1}{6}$	1.0611872	1.0595145	1.0595343	1.0586538	1.0594964

Table 2
Result of errors numerical integration method for Eq. (7) by using numerical integration calculator

Step Sizes	Trapezoidal Rule	Simpson's 1/3 Rule	Simpson's 3/8 Rule	Midpoint Rule	Gauss Quadrature Rule
$\frac{1}{30}$	6.7775×10^{-5}	2.9109×10^{-8}	6.5347×10^{-8}	3.3885×10^{-5}	1.2149×10^{-9}
$\frac{1}{24}$	0.00010589	7.0976×10^{-8}	1.5914×10^{-7}	5.2939×10^{-5}	2.965×10^{-9}
$\frac{1}{18}$	0.00018823	2.2371×10^{-7}	5.0025×10^{-7}	9.4093×10^{-5}	9.364×10^{-9}
$\frac{1}{12}$	0.00042336	1.1238×10^{-6}	2.495×10^{-6}	0.00021157	4.7306×10^{-8}
$\frac{1}{6}$	0.0016901	1.729×10^{-5}	3.7146×10^{-5}	0.00084334	7.4851×10^{-7}

Based on Figure 2, it clearly shows that as the step size increase, the errors for all three methods increase. However, Gauss Quadrature rule consistently results in the smallest error, regardless of the step size.

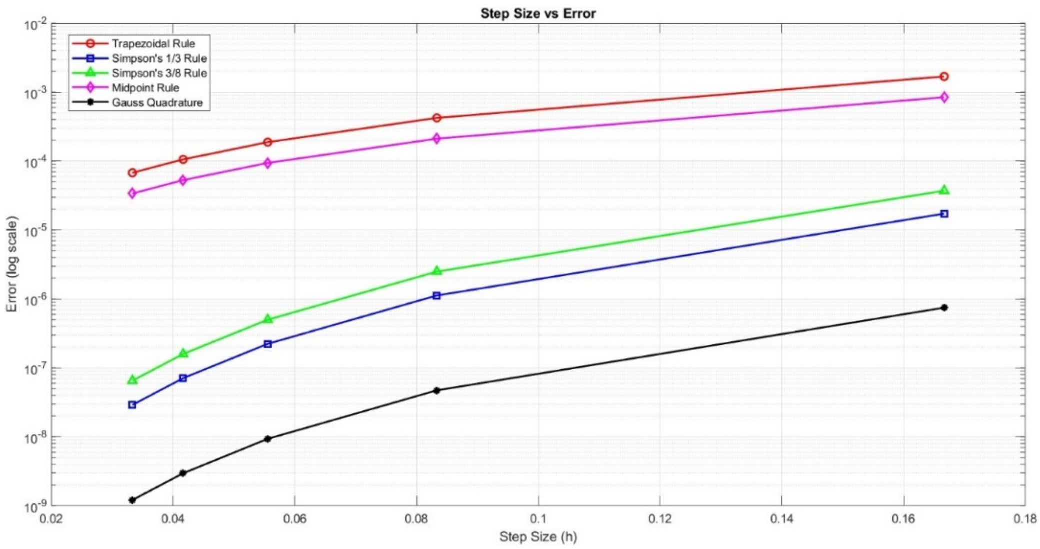

Fig. 2. Graph of relationship between error and step size for Equation (7) when integrating the functions using those methods.

3.1.2 Case 2 (Che Rahim Che The, 2010)

$$\int_0^2 sin(2x)\,(1 + 3\,sin(2x))dx \tag{8}$$

Exact value of Equation (8) is 3.45581247.

Based on Table 3 and Table 4, the results show that Gauss Quadrature consistently provided the best accurate approximations. Even when the step size increase, its accuracy was increase. Other effective method were Simpson's 1/3 Rule and Simpson's 3/8 Rule, especially at lower step sizes. Both approaches produced results with little inaccuracy. However, both of Simpson's approaches are still dependable for everyday use, striking a balance between precision and simplicity of usage. Trapezoidal Rule is more likely to be inaccurate when applied to functions with substantial curvature or nonlinearity since it depends on linear approximations between points. Midpoint Rule yielded the least accurate findings while being computationally straightforward.

Table 3
Result of numerical integration method for equation (8) by using numerical integration calculator

Step Sizes	Trapezoidal Rule	Simpson's 1/3 Rule	Simpson's 3/8 Rule	Midpoint Rule	Gauss Quadrature Rule
$\frac{1}{15}$	3.4567884	3.4558034	3.4557919	3.4553237	3.4558128
$\frac{1}{12}$	3.4573393	3.4557902	3.4557617	3.455047	3.4558134
$\frac{1}{9}$	3.4585345	3.4557414	3.4556481	3.4544449	3.4558154
$\frac{1}{6}$	3.4619865	3.4554402	3.4549196	3.4526921	3.4558273
$\frac{1}{3}$	3.4816252	3.4485628	3.4330176	3.4423477	3.4560616

Table 4
Result of errors numerical integration method for equation (8) by using numerical integration calculator

Step Sizes	Trapezoidal Rule	Simpson's 1/3 Rule	Simpson's 3/8 Rule	Midpoint Rule	Gauss Quadrature Rule
$\frac{1}{15}$	0.0009759	9.0569×10^{-6}	2.0575×10^{-5}	0.00048879	3.7474×10^{-7}
$\frac{1}{12}$	0.0015268	2.2231×10^{-5}	5.0781×10^{-5}	0.00076547	9.1621×10^{-7}
$\frac{1}{9}$	0.002722	7.1087×10^{-5}	0.00016436	0.0013675	2.9046×10^{-6}
$\frac{1}{6}$	0.006174	0.00037227	0.00089286	0.0031203	1.4835×10^{-5}
$\frac{1}{3}$	0.025813	0.0072497	0.022795	0.013465	0.00024916

Figure 3 shows both graphs consistently show that as the step size increase, the errors for all three methods increase.

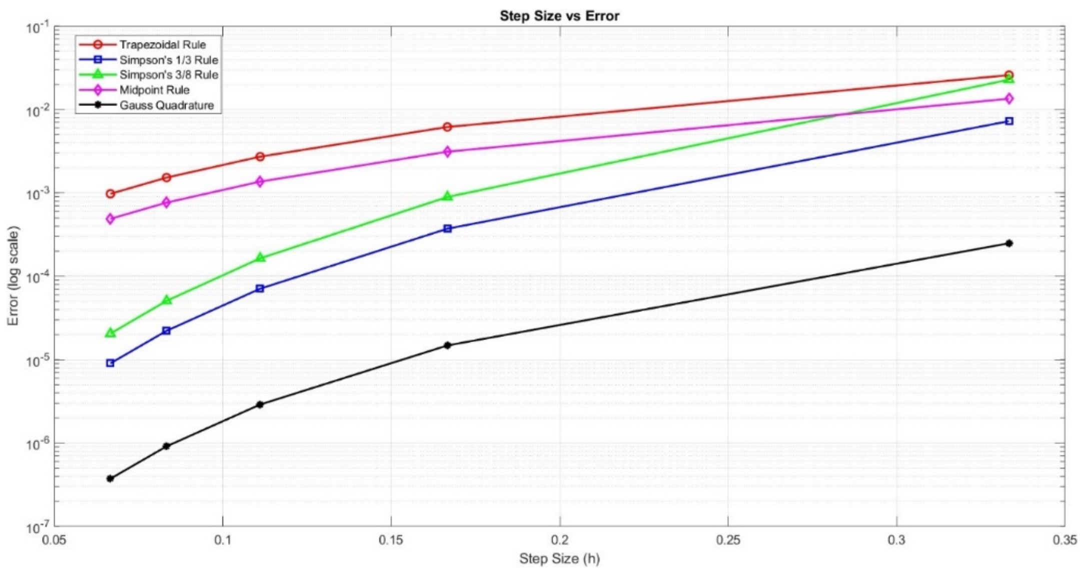

Fig. 3. Graph of relationship between error and step size for Eq. (8).

3.2 Real World Application using Numerical Integration
3.2.1 Drug dosage calculation

Suppose a 500 mg drug is injected as an IV bolus, with $V_d = 50\ L$ and $k = 0.15\ hour^{-1}$ and as the total observation period is 0 to 12 hours, the function of total drug exposure over time will becomes

$$\int_0^{12} C(t)dt = \int_0^{12} \frac{500}{50} \cdot e^{-0.5t}\, dt = \int_0^{12} 10 \cdot e^{-0.15t}\, dt \tag{9}$$

Based on Figure 4, greater drug exposure is often indicated by a larger AUC, which may be associated with a stronger therapeutic impact or, if too high, a risk of toxicity. The result of NIC indicates that the drug's plasma concentration builds up to this total quantity over the course of 24 hours (in concentration × time units, such as $mg \cdot hr/L$).

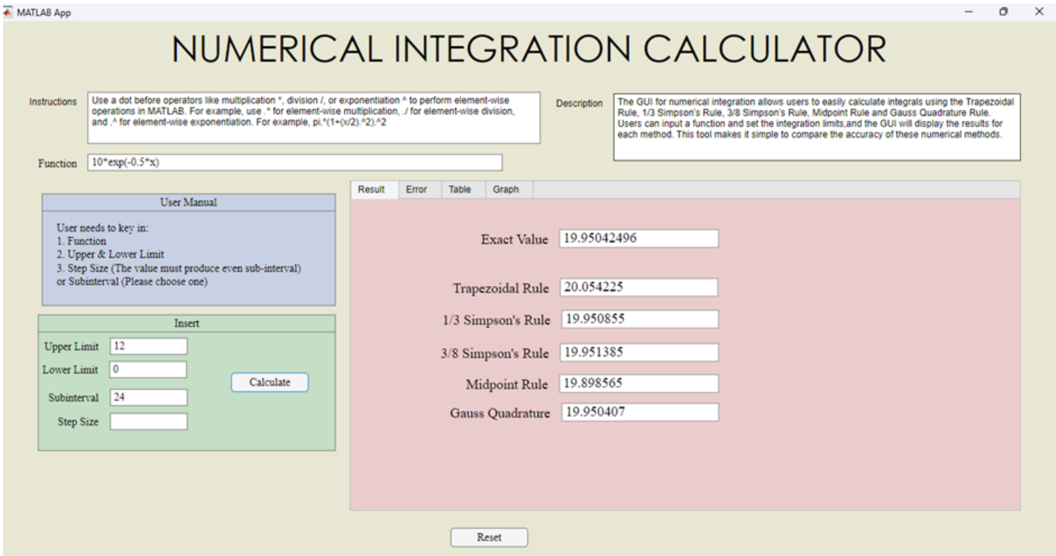

Fig. 4. Results of calculating AUC by using NIC

3.2.2 Option Pricing in Finance

Assume the price of a European call option can be represented as:

$$\int_{100}^{200} f(x)\,dx = \int_{100}^{200} (x-100) \cdot \frac{1}{\sqrt{2\pi}}\, e^{-\frac{1}{2}(x-110)^2} dx \tag{10}$$

Based on Figure 5, it shows that Gauss Quadrature is very useful for smooth functions since it chooses optimal points and weights to evaluate the integral. It is much higher result suggests that it could be able to better capture the function's peak and form than the other approaches.

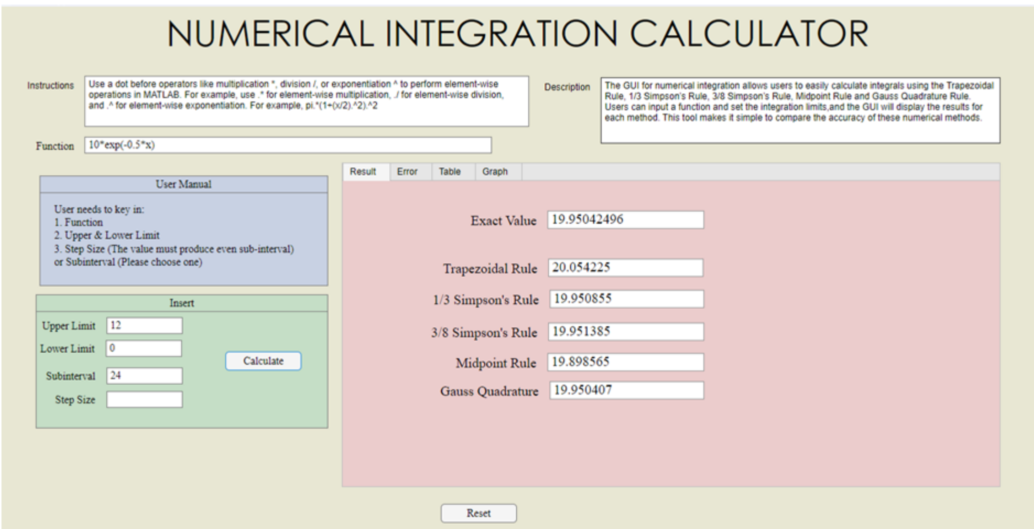

Fig. 5. Results of calculating payoff function by using NIC

4.3.2. Computational Fluid Dynamics

The total volumetric flow rate (Q) can produce by:

$$\int_0^1 f(r)dr = \int_0^1 4\pi r\,(1-r^2)\,dr \tag{11}$$

Based on Figure 6, higher-order approaches like Gauss Quadrature and Simpson's rules proved preferable for smooth functions, particularly in computational fluid dynamics applications, even though all methods produced satisfactory approximations.

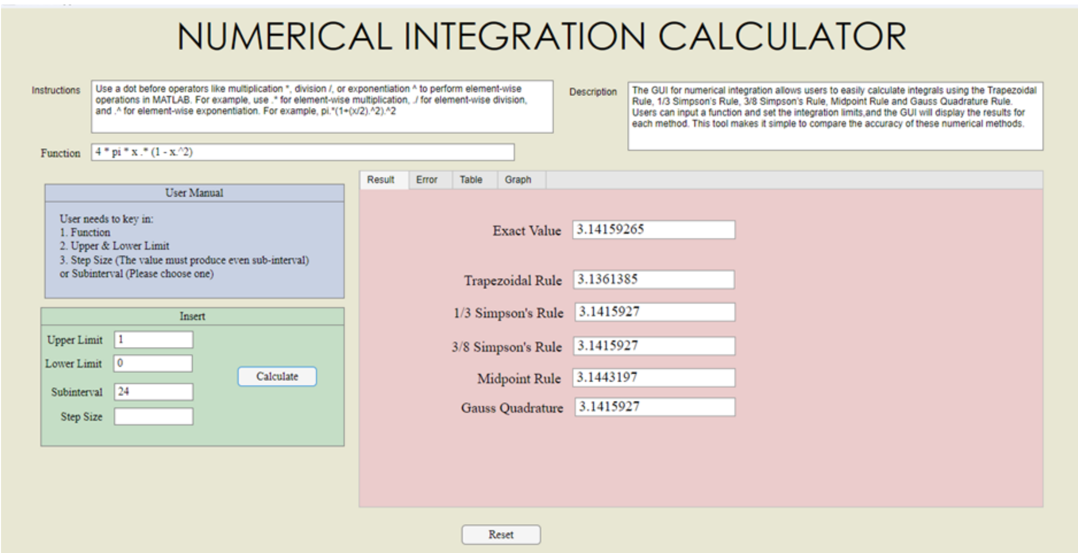

Fig. 6. Results of calculating volumetric flow rate through pipe by using NIC

4. Conclusion

Gauss Quadrature consistently provides the highest accuracy, while Simpson's rules provide a strong balance between performance and precision. Midpoint and Trapezoidal Rules are still useful for basic applications or rough approximations. In real-world situations including pharmacokinetics, finance, and engineering, the GUI also proved to be useful. This project improves user comprehension of numerical integration by providing a useful and instructive tool. Adaptive step size techniques, multidimensional instances, and support for improper integrals are possible future enhancements. Increasing the GUI's usability on online or mobile platforms may also increase its applicability in professional and educational use.

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