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Low-risk cryptocurrency arbitrage trading system

Bachelor's Thesis

Supervisor: Marko Kääramees

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Madalariskiline krüptoraha arbitraaži kauplemise süsteem

Bakalaurusetöö

Juhendaja: Marko Kääramees

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Author’s Declaration of Originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

Cryptocurrency is known as a new type of asset which can be exchanged, used as a payment and, most importantly, traded. Due to the lack of both cryptocurrency regulations and centralization, the price movements of the same asset on different exchanges are not synchronized and such a flaw can be exploited using arbitrage trading. This project aims to implement different cryptocurrency arbitrage trading methods, minimizing the risk using statistical analysis. Although stat-arb strategy implies the price prediction using complex statistical methods, this project aims to use the statistical methods for the successful trading entrance and profit assurance. This project focuses on two arbitrage trading methods: marginal arbitrage and triangular arbitrage. Marginal arbitrage involves marginal trading, or, more precisely, trading using borrowed assets from other parties. Triangular arbitrage involves making consecutive trades starting and finishing with the same cryptocurrency. Although these two systems' profitability depends upon same market principle, they have different advantages, disadvantages and requirements. Both systems had executed a very small amount of trades, but, nevertheless, there were profitable arbitrage opportunity executions.

This thesis is written in the English language and is 34 pages long including 4 chapters, 12 figures and 5 tables.

Annotatsioon

Madalariskiline krüptoraha arbitraaži kauplemise süsteem

Krüptovaluutat tuntakse kui uut tüüpi vara, mida saab vahetada, kasutada maksevahendina ja mis kõige olulisem – sellega saab kaubelda. Krüptovaluuta regulatsioonide ja tsentraliseerimise puudumise tõttu, pole ühe ja sama vara hinnamuutused erinevatel kauplemisplatvormidel sünkroniseeritud, mistõttu sellist puudust võidakse ära kasutada arbitraažkaubanduse abil. Selle projekti eesmärgiks on rakendada erinevaid krüptovaluuta arbitraažkaubanduse meetodeid, minimaliseerides riski, kasutades selleks statistilist analüüsi. Kuigi stat-arb strateegia eeldab hindade prognoosimist, kasutades keerukaid statistilisi meetodeid, siis käesoleva projekti eesmärgiks on kasutada statistilisi meetodeid, et siseneda edukalt kauplemisse ja kindlustata kasumit. Käesolev projekt keskendub kahele arbitraaži meetodile: marginaalne arbitraaž ja kolmnurkne arbitraaž. Marginaalne arbitraaž sisaldab marginaalset kauplemist, või täpsemalt kauplemist, kus laenatakse varasid teistelt osapooltelt. Kolmnurkne arbitraaž sisaldab järjestikuliste tehingute tegemist, alustades ja lõpetades sama krüptovaluutaga. Kuigi nende kahe süsteemi kasumlikkus sõltub sama turu põhimõttest, on neil erinevad eelised, puudused ja nõuded. Kuigi mõlemad süsteemid olid teostanud väga väikse osa tehingutest, olid teostatud kasumlikud arbitraaži võimalused.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 34 leheküljel, 4 peatükki, 12 joonist, 5 tabelit.

List of abbreviations and terms

API	Application Program Interface
BCH	Cryptocurrency “Bitcoin Cash”
BTC	Cryptocurrency “Bitcoin”
BTG	Cryptocurrency “Bitcoin Gold”
CORS	Cross-Origin Resource Sharing
Crypto	Digital (or Cryptographic)
DDoS	Distributed denial-of-service
ETH	Cryptocurrency “Ethereum”
EUR	The euro
Forex	Foreign exchange
GPU	Graphics Processing Unit
HTTP	Hypertext Transfer Protocol
IP	Internet Protocol
JSON	JavaScript Object Notation
Stat-arb	Statistical arbitrage
URL	Uniform Resource Locator
USD	US Dollar
USDT	Cryptocurrency “Tether”
XRP	Cryptocurrency “Ripple”

Table of contents

List of figures

List of tables

1. Introduction

1.1 Background

Cryptocurrency is a new, purely technological, form of currency which can be easily exchanged or used as a payment for goods or services at some places without any intermediate regulatory. Cryptocurrency is based on a revolutionary technology called „Blockchain“ which cryptographically links and secures continuously growing list of records (transactions in this case) known as „blocks“. This technology allows to create a decentralized system, thus attracting plenty of sectors such as banking, government, healthcare [1].

First decentralized cryptocurrency is Bitcoin, released in January 2009 at a price of almost 0. Since November 2013 until January 2017 Bitcoin's price had been fluctuating between 400 and 1000 USD. Year 2017 had become the revolutionary year for the crypto-market and the blockchain as total cryptocurrency market capitalization has increased from 20 million USD to 500 million USD [2].

Figure 1. Bitcoin's price movement. (Source: [2])

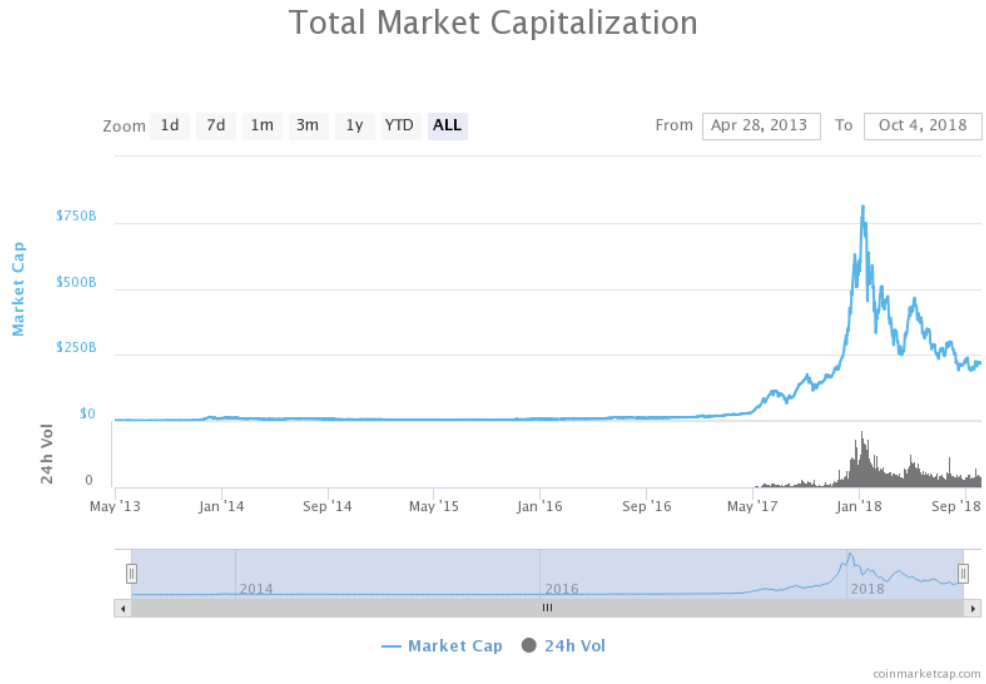

Figure 2. Cryptocurrency overall market capitalization since April 2013. (Source: [2])

Although Bitcoin's market dominance has rapidly dropped to 33% (as of 12. January 2018), it is still known as a cryptocurrency pioneer and the base cryptocurrency. Ethereum (ETH), Ripple (XRP) and Bitcoin Cash (BCH) compose almost same amount of market share (as of March 2018), thus making them most tradable and popular assets. As of 4. October 2018, there are over 2000 cryptocurrencies making the total capitalization of about $220 billion [2].

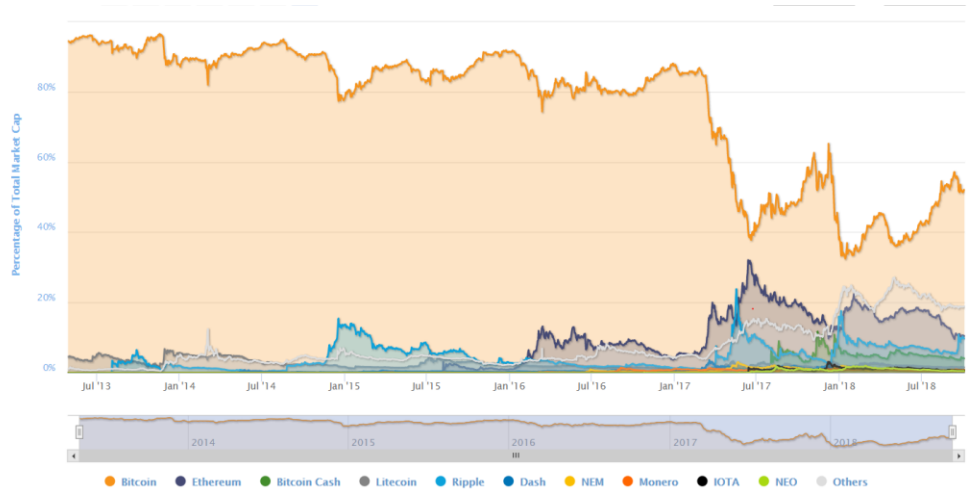

Figure 3. Cryptocurrencies' dominance in cryptocurrency market (Source: [2])

1.2 Motivation

Due to the strict governmental regulations and administrations of the fiat money and the currency circulation altogether, cryptocurrency brings wide range of opportunities for the information technology developers. It is possible to easily create worldwide transactions or a digital wallet for a cryptocurrency storage. Moreover, it is possible to implement both basic and advanced blockchain structures for any problem solution.

Cryptocurrency is a new technology which everybody looks for a profit from. Businessmen – though intermediations (such as cryptocurrency exchanges) and individuals – through smart trading. Such a technological advancement originates wide range of opportunities for cryptocurrency transfers, exchanges and trading which should be made use of.

With the rise of cryptocurrencies, truly new investment sector has been created. Plenty of medium and large sized investors are looking for a profitable cryptocurrency trading system which could double their investments in a short time with a very low risk. Moreover, it is a new sector for quantitative analysts, developers and automated trading.

1.3 Current Solutions

Cryptocurrency enthusiasts have already implemented numerous open-source automated cryptocurrency arbitrage trading projects, however the majority of them have plenty of limitations, such as narrow range of possible currencies and/or exchanges [5]. Arbitrage trading is popular on the cryptocurrency market as it is believed to be „risk-free“ (or market-neutral) trading strategy. Customizable low-risk ready-made trading systems are hardly possible to find as such systems are in use by the financial institutions which develop complex trading strategies and gain good profits.

1.4 Problem Statement

Cryptocurrencies bring in a huge competition to the regular fiat currencies as it is decentralized and has no inflation or deflation [7]. Additionally, there are over 2000 cryptocurrencies and over 200 cryptocurrency exchanges as of December 2018, which results in over 16000 different markets which one can place orders on [2]. Such a wide novel market results, however, in having different prices on the same cryptocurrency on different exchanges at the same moment. Such flaws are able to allow arbitrage trading. Arbitrage trading opportunity occurs when different exchanges offer different prices on the same asset at the same moment. Such a flaw

can be exploited through buying particular cryptocurrency on the exchange offering the lowest price and selling it afterwards on the exchange offering the highest price. The profit's deduction primarily depends on the exchanges' withdrawal, deposit and trading fees. This project aims to build cryptocurrency arbitrage trading system and therefore, thorough understanding of each component is required.

Theoretical background chapter explains the theory behind cryptocurrency and its trading. It analyzes arbitrage trading techniques and provides necessary formulas for different calculations. Next chapter called "Implementation" describes programming tools used in this project and gives a detailed summary of both systems. Last chapter called "Conclusion" summarizes to the project, compares two systems and gives information about further possible way to progress.

2. Theoretical Background

2.1 Cryptocurrency overview

Cryptocurrency is a new currency based on peer-to-peer electronic cash system. Cryptocurrency transactions' signatures must be verified in order to be placed on the network. Such verifications are made by calculating a complex mathematical puzzle, more precisely guessing the number so, that it would correspond to the transaction's hash. Correct calculations are rewarded by the particular amount of the particular cryptocurrency. Such an activity is called „mining" and requires high computing power as long as plenty of electricity. Block verification calculations' difficulty is constantly increasing (every 2016 blocks) while the rewards are dropping. [3]

2.2 Cryptocurrency trading overview

Cryptocurrency trading principle is the same as with stock or foreign exchange trading - buying and selling various assets which are in this case - cryptocurrencies. Unlike the stock market or foreign exchange, cryptocurrency trading is allowed at every moment every day and are never paused. Buy orders are required to be executed in order to buy the cryptocurrency and sell orders are required to be executed in order to sell the cryptocurrency. Although cryptocurrency regulations are very limited [4] and is not yet considered to be a legal financial instrument, it can be said that the first step of financial transaction for obtaining the required asset is an order. Price and amount must be specified for a correct order placement.

2.3 Order types

There are two basic trading orders: Market and Limit orders. Market order's price is set automatically by the exchange and has a high likelihood to be successfully executed. However, market order's price may change significantly depending on the market flow, timing, order size and asset liquidity. Limit order's price, in the meantime, has to be set manually and will be executed as soon market conditions will correspond to the order's price or better in respect to the trader. Otherwise, order will be kept in the order book until somebody will fill it. Limit orders seem to be more reliable as their price is unchangeable and predetermined.

2.4 Order book

In order for order to be successfully executed, it should be matched with pending orders kept in the order book. There are two types of order books: buy order book - keeping buy pending orders and sell order book - keeping sell pending orders. Orders in the order books are kept in the sorted order: from the lowest price to the highest for sell order book and from the highest price to the lowest price for the buy order book.

0.00008149	4,965	0.40459785	0.00008122	1,527	0.12402294
0.00008148	3,760	0.30636480	0.00008121	11,519	0.93545799
0.00008147	1,069	0.08709143	0.00008115	331	0.02686065
0.00008146	608	0.04952768	0.00008114	7,654	0.62104556
0.00008145	6,098	0.49668210	0.00008113	392	0.03180296
0.00008144	6,195	0.50452080	0.00008111	10,849	0.87996239
0.00008143	1,552	0.12637936	0.00008110	12,813	1.03913430
0.00008140	2,768	0.22531520	0.00008106	949	0.07692594
0.00008139	11,245	0.91523055	0.00008105	9,825	0.79631625
0.00008138	23	0.00187174	0.00008104	20,752	1.68174208
0.00008137	8,062	0.65600494	0.00008103	155	0.01255965
0.00008136	3,450	0.28069200	0.00008102	424	0.03435248
0.00008135	1,387	0.11283245	0.00008101	10,245	0.82994745
0.00008133	941	0.07653153	0.00008100	2,829	0.22914900
0.00008131	20	0.00162620	0.00008099	497	0.04025203
0.00008130	380	0.03089400	0.00008097	2,499	0.20234403
0.00008125	309	0.02510625	0.00008096	10,337	0.83688352

Table 1. XRP/BTC orderbook as of 4. October 2018 (on the left side are sell order, on the right side – buy orders). Columns order: Price, Amount, Bitcoin volume (Source: https://binance.com)

For example, there are two pending orders in the sell order book for pair BTC/USD: First - selling 1 BTC at 6000 USD, second one - selling 1 more BTC at 6500 USD. In order to buy instantly 2 BTC, limit order should be placed with amount of 2 BTC and the price of 6500 USD. After placing this order both orders in order book will be matched and 2 BTC will be acquired at an average price of 6250 USD.

2.5 Margin trading

Margin trading often implies high risk trading as term “margin” implies such terms like “loan” and “borrow”. High-risk trading is considered to be trading on leverage. It means borrowing some amount of capital from the exchange in order to increase profits, in the meantime however, increasing losses.

For example, exchange 1 provides 100:1 leverage for BTC/USD whose price is 6000 USD for 1 BTC. Assuming no trading fees and the capital of 60 USD, 0.01 BTC can be bought. Thus, each 10 USD price change of BTC/USD will result in 1 USD profit or loss. In order to lose the whole capital, BTC/USD should drop by 600 USD. Using maximal leverage (100:1) assumes the capital to be 100 times 60 USD, resulting in 6000 USD. Therefore, 1 BTC can be bought and each 10 USD BTC/USD price change will result in 10 USD profit or loss. In order to lost the whole capital using trading on leverage, BTC/USD should drop only by 60 USD.

Second method of margin trading implies borrowing capital from other exchange’s clients. Margin fees apply while borrowing other people’s capital.
For example, the trader is assured that price of BTC/USD will rapidly drop by 1000 USD to 5000 USD per 1 BTC, however he/she has only USD balance. Assuming no trading and margin fees, it is required to sell 1 BTC for the current price of 6000 USD and the buy back 1 BTC for 5000 USD, resulting in profit of 1000 USD. Using margin trading it is possible to borrow 1 BTC (assuming trader’s balance is more than 6000 USD) at the current price of 6000 USD, sell it for 6000 USD, buy it back for 5000 USD and return 1 BTC to the loaner, resulting in the profit of 1000 USD.

2.6 Fees

Exchange fees play main role during cryptocurrency trading as it is exchanges’ main source of income and it would be much easier for clients to profit from the trading without any fees.

2.6.1 Trading fees

Trading fees vary from exchange to exchange and depend upon trading volume and the type of trading. In other words, the more you trade, the less you pay fees. In addition to that, there are two types of trading fees: maker and taker fees.

Maker fees assume that the order makes the liquidity, in other words, it is added to the pending orders which are kept in the order book.

Taker fees assume the order takes the liquidity off the market which means that such an order matches pending orders kept in the order book and is executed instantly.

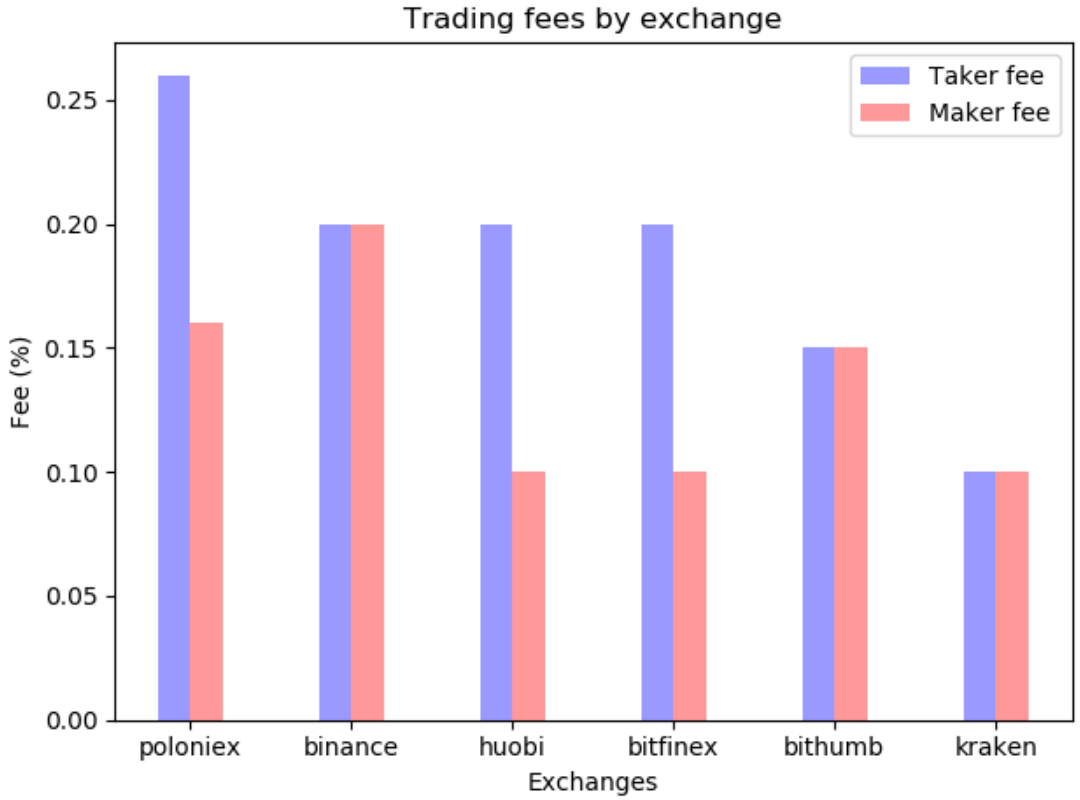

Figure 4. Taker and maker fees on different cryptocurrency exchanges.

2.6.2 Other fees

Besides the trading fees, there are 3 more types of fees taken on the exchange:

- Deposit fees - fees taken from the deposited amount of currency to the exchange
- Withdrawal fees - fees taken from the amount of currency withdrawn from the exchange.
- Margin fees - fees are charged when margin trading.

2.7 Cryptocurrency arbitrage trading overview

Arbitrage is an economics term meaning buying cheap and selling more expensive the same equity in the same moment of time in two different places where the quote prices are different. As virtual coins' price is not regulated by a central bank or a single exchange, it is possible to

find different prices on the same cryptocurrency on different exchanges [8]. In order to take advantage of an arbitrage opportunity, buying at the low price on one exchange and then selling at the higher price on the other exchange should be made.

For example, BTC/USD price on exchange 1 is 6000 USD whereas price on exchange 2 is 7000 USD, thus resulting in the price difference of 1000 USD (or 16.67%). Assuming that there are no trading, deposit and withdrawal fees, 1 BTC can be bought for 6000 USD on the exchange 1, then transferred to the exchange 2 and sold for 7000 USD on the exchange 2, resulting in profit of 1000 USD.

The above-mentioned strategy is not very much reliable as time of transferring cryptocurrency from one exchange to another is undetermined. Moreover, autonomous system will require the withdrawal rights which is very risky to provide as intruders will have the ability to withdraw the funds to their wallets.

2.7.1 Cryptocurrency arbitrate trading strategy

As the cryptocurrency transfers', withdrawals' and deposits' time is undetermined, author chose to use margin trading alongside with hedging strategy. Hedging is a protective type of investment for the current profit assurance by placing opposite orders [9]. As hedging implies selling asset after it is bought, margin trading is required in order to borrow this asset for the sell possibility.

If the price difference of the particular cryptocurrency on different exchanges is high enough, it is required to place a buy order on the exchange offering the lowest price and sell order on the exchange offering the highest price for a potential profit. In order to obtain this profit, opposite orders on both exchanges are required to be executed in order to close all opened positions.

It should be noticed that on both cryptocurrency exchanges offering the lowest and the highest price, both orders – buy and sell orders – are required to be executed. On foreign exchange market, difference between the buy and sell price is called spread which can be provided by the broker in a predetermined way. Although the spread may increase significantly during market opening or unexpected news release, it can be offered as a fixed one by some brokers.

This is because forex trading volume is huge and total market capitalization is even greater, about 5.09 trillion US dollars per day as of April 2016 [10]. Cryptocurrency total market capitalization is about $220 billion with daily volume of about $13.4 billion as of 2. October 2018 [2]. Due to cryptocurrency market's diminutiveness in comparison with any other financial fields, predetermined buy and sell prices' difference (known as spread) is not yet possible [6]. Thus, buy and sell prices difference depends entirely upon the trading volume and the liquidity.

Following diagrams illustrate how trading volume influence the difference between buy and sell prices:

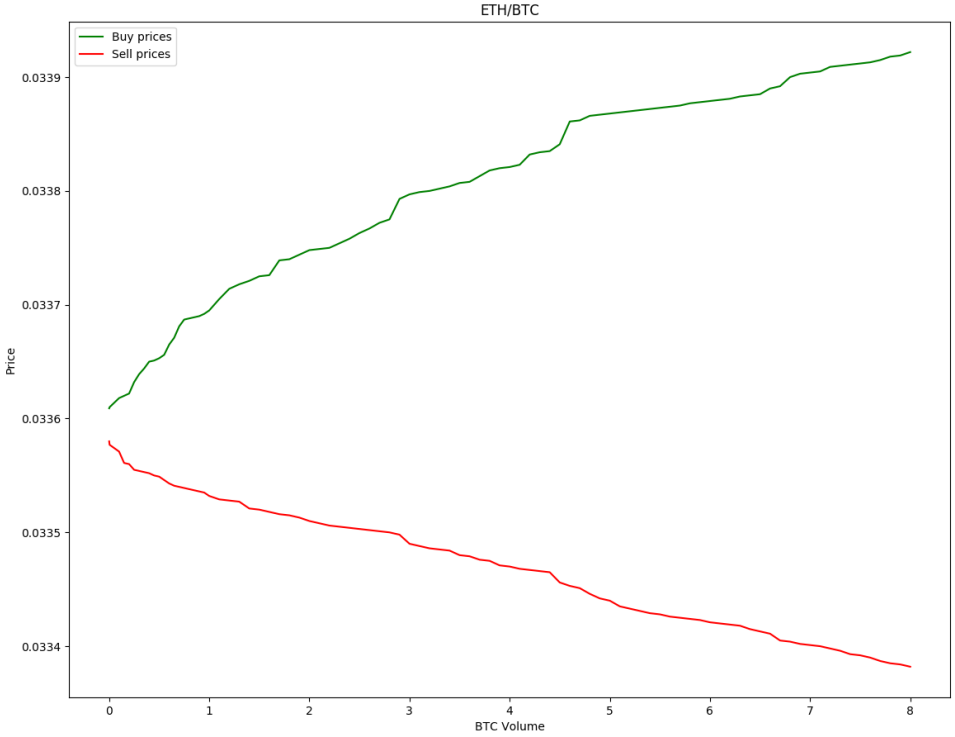

Figure 5. ETH/BTC buy and sell prices in relation to the trading volume.

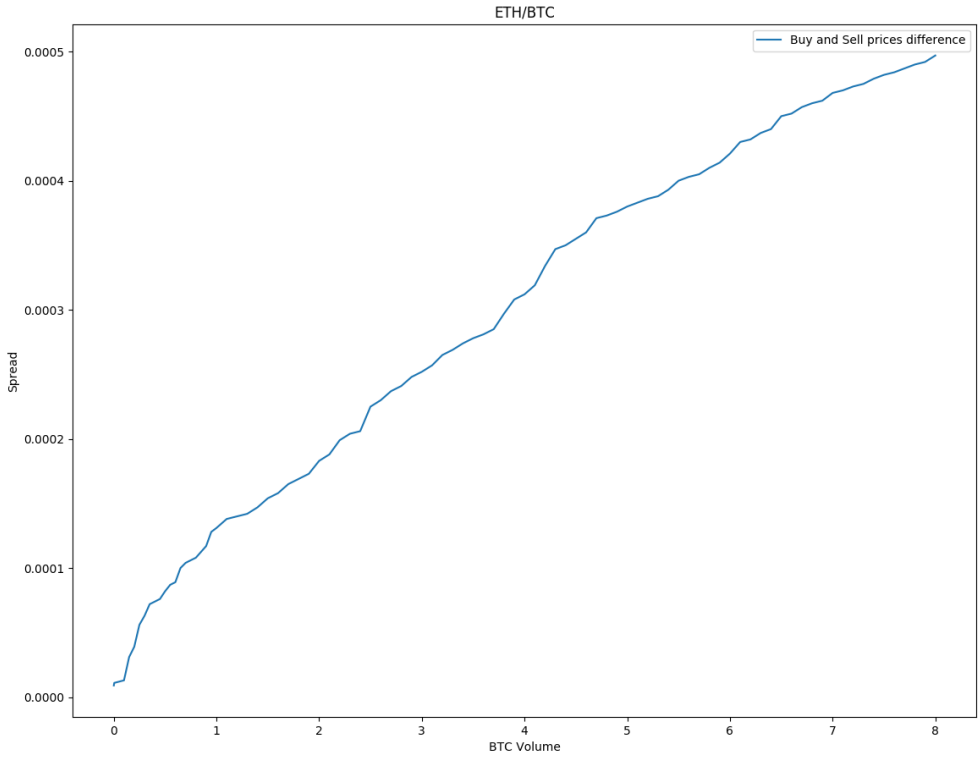

Figure 6. ETH/BTC buy and sell prices difference in relation to the trading volume.

Using linear regression, it can be determined that buy and sell prices' differences grow linearly as Pearson correlation coefficient is equal to 0.9882 [17].

2.7.2 Calculations

Arbitrage strategy implies having same cryptocurrency (BTC) on all exchanges and buying the particular amount (N) of other cryptocurrencies ($Coin$) on the exchange 1 at a lower price (P_1) with trading fee (F_1) and selling it on the exchange 2 at a higher price (P_2) with trading fee (F_2). As our strategy requires instant order fulfillment, orders' type is chosen to be the limit orders and trading fees' types are "taker fees" as system tries not to add orders to order books.

Following table declares all the required variables for calculations and their definitions:

Variable	Definition
X	Maximal bitcoin balance having on each exchange.

X_1'	Required amount of bitcoins on the exchange offering lower price
X_2'	Required amount of bitcoins on the exchange offering higher price
P_1	Lowest price of the asset on the particular exchange. This price is used for buying an asset.
P_1'	Price of the particular asset on the exchange having offered lower price. This price is used for selling an asset.
F_1	Trading fee on the exchange offering lower price on the particular asset.
N_1	The required amount of an asset to be bought on the exchange offering lower price on that asset.
P_2	Highest price of the asset on the particular exchange. This price is used for selling an asset.
P_2'	Price of the particular asset on the exchange having offered higher price. This price is used for buying an asset.
F_2	Trading fee on the exchange offering higher price on the particular asset.
N_2	The required amount of an asset to be sold on the exchange offering higher price on that asset.
D_1	Difference between P_1 and P_2.
D_2	Difference between P_1' and P_2'.
C	Price change of an asset on the exchange having offered lower price.

Table 2. Variables and definitions.

Considering having initially X of BTC on all chosen exchanges, buy order equation is following:

$$X_1' = N_1 * P_1 * (1 - F_1),$$
$$where \begin{cases} X_1' \text{ is the required amount of } BTC \text{ on exchange } 1 \\ N_1 \text{ is the amount of } Coin \text{ to be bought on exchange } 1 \end{cases} \quad (1)$$

And sell order equation is following:

$$X_2' = N_2 * P_2 * (1 - F_2),$$
$$where \begin{cases} X_2' \text{ is the required amount of } BTC \text{ on exchange } 2 \\ N_2 \text{ is the amount of } Coin \text{ to be sold on exchange } 2 \end{cases} \quad (2)$$

In the case of buy order, the required amount of BTC is deducted from the initial balance, whereas in the case of sell order, the required amount of BTC is added to the initial balance, creating a loan of N_2 of $Coin$.

As we are buying other cryptocurrency using our whole capital, the required amount of BTC is equal to the initial capital X. Moreover, as chosen arbitrage strategy uses borrowing funds, trading fees are not charged when placing margin sell order of borrowed funds.

Thus, the amount of trading cryptocurrency can be calculated as follows:

$$N_1 = \frac{X}{P_1} \quad (3)$$

$$N_2 = N_1 * (1 - F_1) \quad (4)$$

Exchange 1 offering **lower** price on the particular cryptocurrency ($Coin$)	**Exchange 2** offering **higher** price on same cryptocurrency ($Coin$)
$Balance_{10} = \begin{cases} X \text{ of } BTC \\ 0 \text{ of } Coin \end{cases}$	$Balance_{20} = \begin{cases} X \text{ of } BTC \\ 0 \text{ of } Coin \end{cases}$
Order: BUY N_1 of $Coin$ at P_1	**Order: SELL N_2 of $Coin$ at P_2**

$Balance_{11} = \begin{cases} X - N_1 * P_1 \ of \ BTC \\ N_1 * (1 - F_1) \ of \ Coin \end{cases}$	$Balance_{21} = \begin{cases} X + N_2 * P_2 \ of \ BTC \\ -N_2 \ of \ Coin \end{cases}$
Order: SELL $N_1 * (1 - F_1)$ of Coin at P_1'	**Order: BUY $\frac{N_2}{(1-F_2)}$ of Coin at P_2'**
$Balance_{12} = \begin{cases} X - N_1 * P_1 + N_1 * P_1' * (1 - F_1)^2 \ of \ BTC \\ 0 \ of \ Coin \end{cases}$	$Balance_{22} = \begin{cases} X + N_2 * P_2 - \frac{N_2 * P_2'}{1 - F_2} \ of \ BTC \\ 0 \ of \ Coin \end{cases}$

Table 3. Marginal arbitrage trading steps with formulas.

The table above neglects margin fees such as lending rates as they appear to be insignificant due to their low percentage (between 0.001% and 0.15%) and considering initially lower profit than it could be by using higher than real prices for buying and lower than real prices for selling.

Showing the above-mentioned calculations, following example can be used. Considering Bitcoin prices on exchanges to be \$8000 and \$9000, equal trading fees of 0.2%, final price to be \$10000 and initial balance on each exchange to be \$9000, following calculations can be made:

$$P_1 = 8000$$
$$P_2 = 9000$$
$$F_1 = F_2 = 0.002$$
$$P_1' = P_2' = 10000$$

$$N_1 = \frac{9000}{8000} = 1.125$$
$$N_2 = 1.125 * (1 - 0.002) = 1.12275$$

$$Balance_{12} = \begin{cases} 9000 - 1.125 * 8000 + 1.125 * 10000 * (1 - 0.002)^2 = \ 11205.045 \ \$ \\ 0 \ of \ BTC \end{cases}$$

$$Balance_{22} = \begin{cases} 9000 + 1.12275 * 9000 - \dfrac{1.12275 * 10000}{1 - 0.002} = 7854.75\ \$ \\ 0\ of\ BTC \end{cases}$$

$$Initial\ balance = 2 * 9000 = 18000\ \$$$
$$Ending\ balance = 11205.045 + 7854.75 = 19059.795\ \$$$

$$Profit = 19059.795 - 18000 = 1059.795\ which\ is\ \frac{1059.795}{18000} * 100\% = 5.88775\%$$

It is required to define important price differences which mostly influence the profit. First main price difference is the price difference (D_1) between buy price on the exchange offering lower price and sell price on the exchange offering higher price. Second main price difference is the price difference (D_2) between sell price on the exchange offering lower price and buy price on the exchange offering higher price.

$$D_1 = \frac{P_2 - P_1}{P_1} \tag{5}$$

$$D_2 = \frac{P_2' - P_1'}{P_1'} \tag{6}$$

Considering starting and ending balances it is possible to create a profit formula as follows:

$$Balance_{start} = 2X \tag{7}$$

$$Balance_{end} = Balance_{12} + Balance_{22} \tag{8}$$

$$Profit = \frac{Balance_{end} - Balance_{start}}{Balance_{start}} \tag{9}$$

Substituting the general variables with their corresponding equations, profit formula transforms in the following one:

$$Profit = \frac{X - N_1 * P_1 + N_1 * P_1' * (1 - F_1)^2 + X + N_2 * P_2 - \frac{N_2 * P_2'}{1 - F_2} - 2X}{2X} \tag{10}$$

Reducing X in numerator and substituting N_2, formula simplifies to:

$$Profit = \frac{N_1}{2X} * \left[-P_1 + P_1' * (1 - F_1)^2 + (1 - F_1) * P_2 - \frac{(1 - F_1) * P_2'}{1 - F_2} \right] \tag{11}$$

Introducing D_1 and D_2 to P_2 and P_2', respectively, where

$$P_2 = P_1 * (1 + D_1) \tag{12}$$

$$P_2' = P_1' * (1 + D_2) \tag{13}$$

profit formula changes to:

$$Profit = \frac{N_1}{2X} * \left[-P_1 + P_1' * (1 - F_1)^2 + P_1 * (1 - F_1) * (1 + D_1) - \frac{P_1' * (1 - F_1) * (1 + D_2)}{1 - F_2} \right] \tag{14}$$

Grouping P_1 and P_1' alongside with $(1 - F_1)$ as follows:

$$Profit = \frac{N_1 * (1 - F_1)}{2X} * \left[P_1 (1 + D_1 - \frac{1}{1 - F_1}) + P_1' (1 - F_1 - \frac{1 + D_2}{1 - F_2}) \right] \tag{15}$$

And introducing the price change (C) where

$$C = \frac{P_1' - P_1}{P_1} \;\rightarrow\; P_1' = P_1 * (1 + C), \qquad where\ C \in [-1, \infty) \tag{16}$$

profit formula becomes following:

$$Profit = \frac{N_1 * P_1 * (1 - F_1)}{2X} * \left[1 + D_1 - \frac{1}{1 - F_1} + (1 + C)(1 - F_1 - \frac{1 + D_2}{1 - F_2}) \right] \tag{17}$$

Moreover, considering that full capital is used, $(N_1 * P_1 = X)$ profit formula simplifies to:

$$Profit = \frac{(1 - F_1)}{2} * \left[1 + D_1 - \frac{1}{1 - F_1} + (1 + C)(1 - F_1 - \frac{1 + D_2}{1 - F_2}) \right] \tag{18}$$

The derivative over the price change (C) is following:

$$\frac{dProfit}{dC} = \frac{(1 - F_1)}{2} * \left[1 - F_1 - \frac{1 + D_2}{1 - F_2}\right] \tag{19}$$

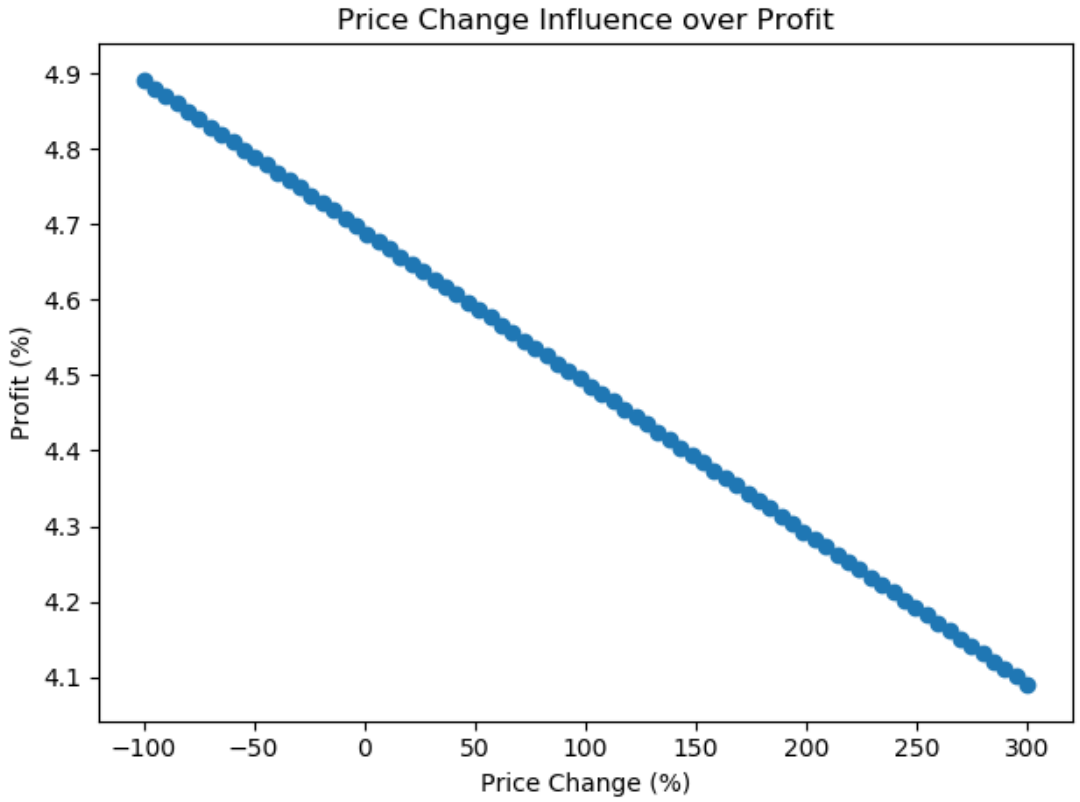

Figure 7. Price change influence over profit.

Figure 7 shows that the more price drop eventually, the more profit can be earned. Or in the other words, the profit is greater if asset price goes down during trades.

The over the starting price difference (D_1) is following:

$$\frac{dProfit}{dD_1} = \frac{1 - F_1}{2} \tag{20}$$

Figure 8. Start prices difference influence over profit.

The derivative over the ending price difference (D_2) is following:

$$\frac{dProfit}{dD_2} = -\frac{(1+C)*(1-F_1)}{2*(1-F_2)} \tag{21}$$

Figure 9. Ending price difference influence over profit.

Second derivatives are equal for all the variables:

$$\frac{d^2Profit}{dC^2} = \frac{dProfit}{dD_1} = \frac{d^2Profit}{dD_2^2} = 0, \tag{22}$$

The derivates (19), (20), (21) and (22) show that price change as long as starting and ending price difference influence the profit linearly.

It can be noticed from the final profit formula different facts:

- The more fees are charged, the less profit becomes
- Profit increases as long as starting difference (D_1) increases
- Profit increases as long as ending difference (D_2) decreases
- Profit is greater if market's trend has been downward $(C < 0)$

2.8 Cryptocurrency triangular arbitrage trading overview

Although triangular arbitrage implies taking advantage of the three exchange rates among three currencies [11], it is possible to take advantage of more than three currencies. Cryptocurrency triangular arbitrage system profits from buying and selling different cryptocurrencies starting and ending with the same one resulting in a greater balance of the first cryptocurrency. It is a different type of arbitrage trading strategy which also profits from the price discrepancy or irregularity. Triangular arbitrage implies finding profitable paths consisting of different cryptocurrencies. This task's problem is similar to Floyd-Warshall algorithms which finds intermediary node so, that the path though such a node becomes shorter [11].
Standard shortest path Floyd-Warshall algorithm pseudocode:

```
1 let matrix be a |V| × |V| array of distances
2 for k from 1 to |V|
3   for i from 1 to |V|
4     for j from 1 to |V|
5       if matrix[i][j] > matrix[i][k] + matrix[k][j]
6           matrix[i][j] ← matrix[i][k] + matrix[k][j]
7       end if
```

Although all price calculations are made using multiplication and all path finding algorithms use weight sums, price's multiplication can be replaced with addition using logarithms of prices. This however raises question about prices' accuracy as it may disappear. Moreover, triangular arbitrage implies longest path problem in directed cyclic graph which is believed to be NP-hard problem meaning that there is no efficient solution [18].

This project aims to build NVIDIA GPU accelerated brute-force path finding algorithm which could return the best path in $O(N^L)$ time, where N is cryptocurrency total count (vertices) and L is the required path length.

For example, XRP/ETH price is P_1, ETH/BTC price is P_2, XRP/BTC price is P_3. In order to calculate the profit for the path XRP -> ETH -> BTC -> XRP, it is required to:

- Sell XRP and get ETH

- Sell ETH and get BTC
- Buy XRP for BTC

Considering no trading fees and having initially N of XRP, the path calculations are made as follows:

- Sell N XRP and get $(N * P_1)$ ETH
- Sell $(N * P_1)$ ETH and get $(N * P_1 * P_2)$ BTC
- Buy N' XRP for $(N * P_1 * P_2)$ BTC where $N' = (N * P_1 * P_2) \div P_3$

Having the balance after all path sequential combinations are traded, the profit percentage can be calculated as follows:

$$Profit = \frac{N' - N}{N} * 100\%, where \begin{cases} N\ is\ the\ initial\ balance \\ N' is\ the\ ending\ balance \end{cases} \quad (23)$$

Replacing N' and N with their corresponding equations, the profit formula can be written as follows:

$$Profit = \left(\frac{\frac{N * P_1 * P_2}{P_3} - N}{N} \right) * 100\% = \left(\frac{P_1 * P_2}{P_3} - 1 \right) * 100\% \quad (24)$$

Considering the market prices as of 4. October 2018 for XRP/ETH, ETH/BTC, XRP/BTC to be 0.002415, 0.034109 and 0.00008230, respectively, profit can be calculated using above-mentioned formula. Although the potential profit is positive (0.089%), it is very small which results in a negative profit if trading fees are considered.

It can be concluded that in the case of sell operation, sell price is multiplied with the amount and in the case of buy operation, buy price is divided with the amount which results in finding the amount of another cryptocurrency.

In order to create required matrices for the brute-force algorithm, 4 matrices with the dimensions of |N| x |N| (where N is the amount of cryptocurrencies allowed in the path) are needed:

1) "action_matrix", showing if it is a buy or sell operation for moving from one cryptocurrency to another.
2) "t_fees_matrix", showing the trading fee while moving from one cryptocurrency to another.
3) "w_fees_matrix", showing the withdrawal fee while moving from one cryptocurrency to the same one but on the different exchange.
4) "matrix", showing the buy and sell prices of the cryptocurrency pair.

For example, XRP maps to 2 and BTC maps to 3. It is known that moving from XRP (base currency) to BTC (quote currency) is a sell operation, and from BTC to XRP – buy operation. It is therefore possible to describe what matrices indices mean:

- Matrix[2][3] will correspond to the sell price of XRP/BTC
- Matrix[3][2] will correspond to the buy price of XRP/BTC
- Action_matrix[2][3] = SELL
- Action_matrix[2][3] = BUY
- W_fees_matrix[2][3] is same as W_fees_matrix[3][2] and is equal to 0
- T_fees_matrix[2][3] is the same as T_fees_matrix[3][2] and is equal to the trading fee, for example 0.998 which implies the trading fee of 0.2% $(100\% - 0.2\%)$

Brute-force algorithm pseudocode for the path length of 4:

```
1  let |V|    be a number of cryptocurrencies allowed in the path
2  let matrix be a |V| × |V| matrix of cryptocurrency prices
3
4  let action_matrix be a |V| × |V| matrix of actions
5  let t_fees_matrix be a |V| × |V| matrix of trading fees
6  let w_fees_matrix be a |V| × |V| matrix of withdrawal fees
7  let balances      be a |V| array of corresponding initial balances
8
9  let best_path   be NONE holding the best path
10 let best_profit be -10 indicating the profit of the best_path
```

```
11
12 for A from 0 to |V| - 1
13   for B from 0 to |V| - 1
14     for C from 0 to |V| - 1
15       for D from 0 to |V| - 1
16         if A, B, C, D are not unique
17           continue
18         let current_path = [A, B, C, D, A]
19         let balance = balances[A]
20         for i from 0 to size(current_path) - 1
21           let from_coin = current_path[i]
22           let to_coin = current_path[i+1]
23           let action = action_matrix[from_coin][to_coin]
24           if action is BUY
25             let move_price = matrix[from_coin][to_coin]
26             if move_price is 0
27               current_path is incorrect
28               continue to the next path
29             let move_fee = t_fees_matrix[from_coin][to_coin]
30             balance = (balance / move_price) * move_fee
31           if action is SELL
32             let move_price = matrix[from_coin][to_coin]
33             if move_price is 0
34               current_path is incorrect
35               continue to the next path
36             let move_fee = t_fees_matrix[from_coin][to_coin]
37             balance = balance * move_price * move_fee
38           if action is WITHDRAW
39             let move_fee = w_fees_matrix[from_coin][to_coin]
40              balance = balance – move_fee
41           if action is NONE
42             current_path is incorrect
43             continue to the next path
44         let path_profit = (balance – balances[A]) / balances[A]
45         if path_profit > best_profit
46           best_profit = path_profit
47           best_path = current_path
48 return best_path
```

As the above-shown brute-force algorithm makes use only of numbers in its computation, it can be upgraded for the computation on GPU.

2.9 Limitations

It is very important to understand all possible limitations with arbitrage trading.

2.9.1 Overall

Cryptocurrency exchanges often suffer for DDoS attacks as they possess high amounts of cryptocurrencies which have their own financial value and are considered to be hard to trace back [12]. For ensuring DDoS protection, exchanges set the limit for the API requests which refreshes each minute. Such an exchanges' security measure limits the frequency of prices' updates.

2.9.2 Arbitrage limitations

Due to the buy and sell prices difference rapid increasement alongside with trading volume increase, arbitrage trading volume is limited. Such a limitation, limits profit increase if trading volume increases.

2.9.3 Triangular arbitrage limitations

Triangular arbitrage requires getting multiple prices of multiple cryptocurrencies on multiple exchanges, thus resulting in too many requests. Even if sending these requests concurrently, it is too much for a single or even two computers. It is required, thus, having a large system only for the price gathering.

2.10 Risks

Cryptocurrency is known as a volatile asset which means that the price may significantly change in a matter of seconds. In addition to that, different cryptocurrency exchanges have different response delay time (latency) which aggravates the risk of misplaced orders. Such an adversity can be evaded setting particular price whilst sending trade orders (limit orders). As two orders are required simultaneously to be successfully executed, order successful execution problem arises. Selling asset requires high liquidity in order for order to be executed immediately without high price change.

3. Implementation

3.1 Environment

Python is a high-level language designed for speed of development providing wide range of libraries, syntax simplicity and high efficiency [16] which makes it perfect for a quantitative finance and data analysis [17]. As this project requires parallel data handling, Python offers excellent asynchronous data processing libraries such as multiprocessing and asyncio. These libraries allow to execute a task without the precedent waiting for the previous task completion. Such an advantage is vital, as a task, sending HTTP request, is idle whilst waiting for the response. In general, the meaning of the word „arbitrage“ already implies parallel actions.

Furthermore, Python is a perfect tool for data science. Data science explores such fields as mathematics, statistics, computer science and machine learning. Libraries such as „NumPy“, „Pandas“ and „Matplotlib“ provide efficient data storage, fast array processing alongside with data visualization on a diagram or chart. These Python’s opportunities allow to create a statistical analysis on any asset including cryptocurrency.

C++ language is a low-level language which can handle GPU programming acceleration. NVIDIA company provides CUDA toolkit which facilitates GPU-accelerated programming [15].

As each exchange provides their own APIs which have different endpoints and response data structures, Python CCXT library is used for unification of over hundred cryptocurrency exchanges [19]. This library is still under heavy development and has enormously advanced during this project’s development. It unifies all the exchanges’ methods using inheritance. For asynchronous HTTP processing it uses Python library “asyncio” which provides single-threaded concurrent code execution.

In order to create Python backend, “Flask” web framework was used as it is fast and easy to use. Alongside with “Flask”, library “Flask_cors” allows to configure CORS settings.

As GPU data processing requires low-level programming language such as C++ or specifically developed by NVIDIA CUDA, library “pycuda” allows C++ code integration inside Python wrapping CUDA API for GPU addressing.

3.2 Arbitrage trading system

3.2.1 General

For creating the best arbitrage trading system numerous machines running on different IP addresses are required as cryptocurrency exchanges' limitations do not allow very frequent price updates. More precisely, it is required to fetch order books from different exchanges and find the prices corresponding to the trading volume. Moreover, separating gathering system from trading system parallelizes price gathering and trading.

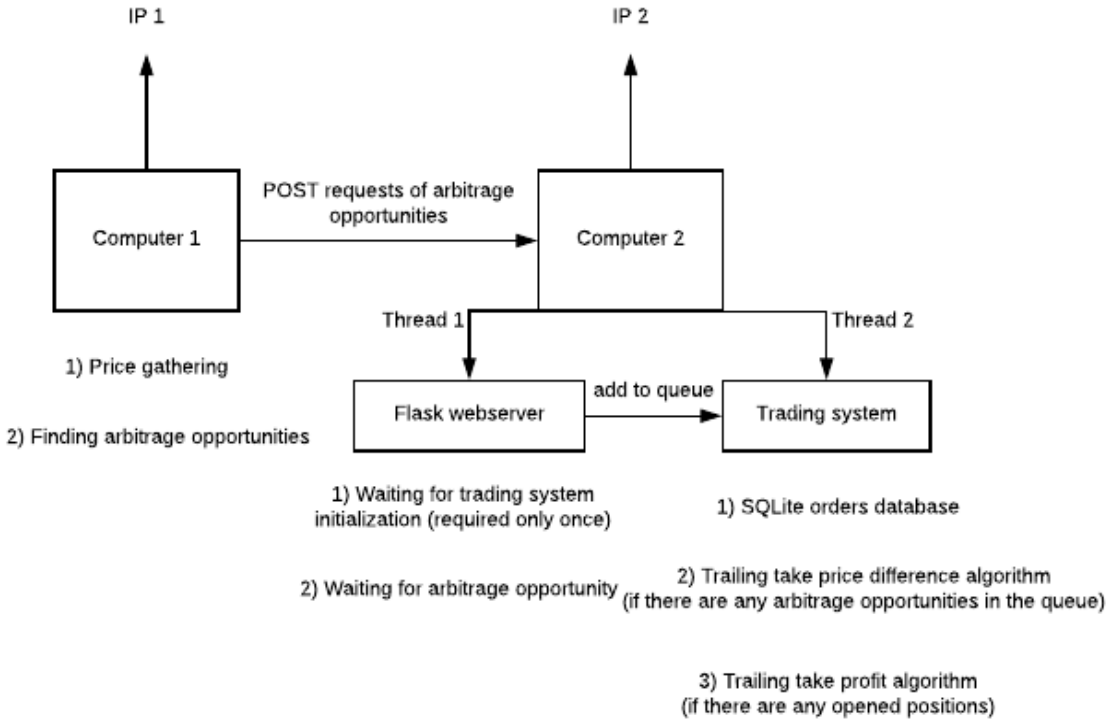

Figure 10. Cryptocurrency arbitrage trading system.

Figure 10 shows which arbitrage trading system author created for the system to be potentially successful. It consists of 2 main systems each having its own task. Left-handed system (Computer 1) is responsible for initialization (such as gathering trading fees), collecting and saving different cryptocurrency prices using proxy and finding arbitrage opportunities. After the arbitrage opportunity is found, left-handed system sends JSON POST request to the right-handed system (Computer 2) where Flask webserver sends it to the trading system. Trading

system sends simultaneous trading requests to the exchanges after assuring the profit still exists and there is enough of residual balance.

The flow of the arbitrage trading system is following:

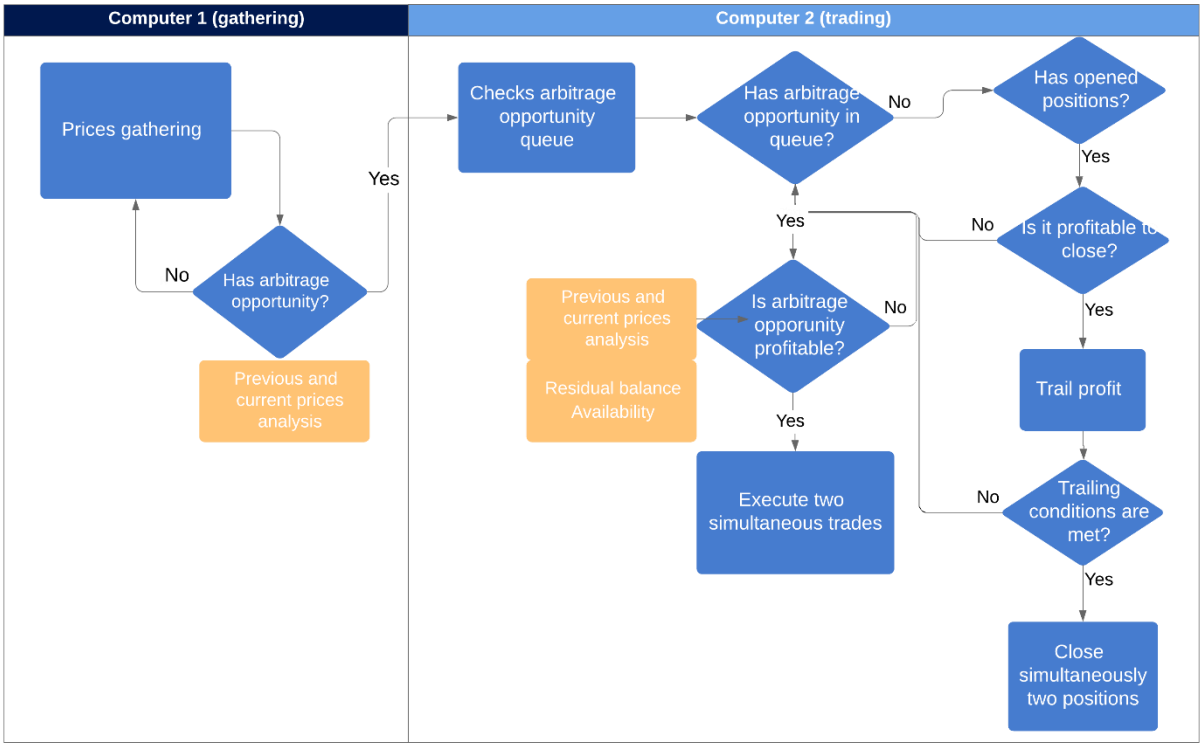

Figure 11. Cryptocurrency arbitrage trading system's flow chart.

3.2.2 Trade opening condition

In order to assure that potential profit exists, profit calculations are to be made. Moreover, price differences' fluctuations are very important as it determines whether it is actually possible to close all the orders after system executes buy and sell order on the corresponding exchanges. In order to assure that the price difference between those exchanges are actually changing enough, weighted arithmetic mean is required to be adopted.

Weighted arithmetic mean returns mean price difference defining following weights:

- 0.65 weight ($w_1 = 0.65$) is pointed to the difference between the current price difference and the worst-case ending difference (x_1), more precisely the maximum ending difference.

$$x_1 = D_1 - MAX(List\ of\ differences\ for\ 1\ hour\ back) \quad (25)$$

- 0.25 weight ($w_2 = 0.25$) is pointed to the difference between the current price difference and the mean ending difference (x_2).

$$x_2 = D_1 - MEAN(List\ of\ differences\ for\ 1\ hour\ back) \quad (26)$$

- 0.1 weight ($w_3 = 0.1$) is pointed to the difference between the current price difference and the best-case ending difference (x_3), more precisely the minimum ending difference.

$$x_3 = D_1 - MIN(List\ of\ differences\ for\ 1\ hour\ back) \quad (27)$$

The above-mentioned weights are chosen randomly, and they determine the entry barrier. The higher weight (w_1) is assigned to the difference between the current price difference and the worst-case ending difference (x_1), the less risk it becomes as it means that current difference is much higher than all the differences there were during past 1 hour.

Weighted arithmetic mean formula looks like as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \quad (28)$$

Considering the total amount of weights is 3 and their sum is 1, the above-shown formula transforms to the following one:

$$\bar{x} = w_1 x_1 + w_2 x_2 + w_3 x_3 \quad (29)$$

If $\bar{x} > 0.8$, current arbitrage opportunity can be considered to be both profitable and efficient.

3.2.3 Trade closing condition

Having opened positions in the portfolio, it is of a great ease to calculate the real profit at each moment of time using profit formula provided in this research. In order to maximize the profit, trailing take profit strategy can be used.

Trailing take profit strategy trails the profit at each moment of time and sets the profit which the system will take at 5% below the current one. If current profit raises, take profit also raises. If current profit drops, take profit does not change. If current profit reaches take profit ($\pm 3\%$), closing orders are executed and maximized profit is achieved.

3.3 Triangular arbitrage trading system

Triangular arbitrage requires sequential cryptocurrencies' buying and selling. As prices' changes happen constantly, it is of a high probability that last required trades in the path will not be successfully executed. In order to circumvent such an adversity, it is possible to use cryptocurrencies which are owned beforehand. In this case, it is possible to send orders in parallel without waiting for other orders' fulfillment. After all orders' successful execution, profit will be made, and balances will return to their places, thus allowing to continue trading.

Triangular arbitrage trading system consists of following parts:

1) Initialization
    - Mapping each cryptocurrency to a number starting from zero
    - Filling deposit, withdraw and trading fees in the matrices
    - Filling action matrix with corresponding actions mapped to numbers
2) Gathering prices
    - Collecting all the prices of owned cryptocurrencies on different exchanges simultaneously using reverse proxy
    - Filling price matrix with corresponding prices
3) Algorithm
    - Running all the matrices through GPU accelerated brute-force algorithm and finding the most profitable path
4) Examination
    - Checking if found path is still profitable
5) Trading
    - If found path is profitable, simultaneous orders are sent to the exchange(s)

4. Conclusion

The aim of this project was to build two systems both of which determine cryptocurrency arbitrage trading opportunity. Following table describes both systems' functionality and requirements:

	Marginal arbitrage	Triangular arbitrage
Requires multiple of different assets to be held ("no" is better)	NO	YES
Requires more than 10 simultaneous price updates ("no" is better)	NO	YES
Uses marginal trading ("no" is better)	YES	NO
Requires more than one machine ("no" is better)	YES	NO
Each trade volume is: ("higher" is better)	HIGHER	LOWER
Risk source (the less there are risk sources, the better it is)	Fast price fluctuations Main cryptocurrency price drop Low price differences' fluctuations	Fast price fluctuations Multiple cryptocurrency price drop
Requires NVIDIA GPU ("no" is better)	NO	YES
Immediate potential profit ("yes" is better)	NO	YES

Table 4. Marginal and triangular arbitrage trading systems' comparison table.

4.1 Marginal arbitrage trading system results

Although it is required to test both systems on real time data for at least 3 months, there were some successful executions. Marginal arbitrage trading system bought 30.56874 Bitcoin Gold (BTG) for Bitcoin (BTC) on the exchange called "Huobi" and sold the same amount on the exchange called "Bitfinex" with similar trading fees of 0.2% on 7. August 2018 at 19:07:21 with prices 0.003449 and 0.0035079, respectively. Opposite orders were executed in approximate 16.5 hours on 8. August 2018 at 11:38:33 with prices 0.003375 and 0.0034038, respectively.

Considering this information, theoretical and practical results can be compared using provided formulas in (5), (6), (16) and (18):

$$P_1 = 0.003449$$
$$P_2 = 0.0035079$$
$$P_1' = 0.003375$$
$$P_2' = 0.0034038$$
$$F_1 = 0.002$$
$$F_2 = 0.002$$

$$D_1 = \frac{0.0035079 - 0.003449}{0.003449} = 0.017077$$
$$D_2 = \frac{0.0034038 - 0.003375}{0.003375} = 0.008533$$
$$C = \frac{0.003375 - 0.003449}{0.003449} = -0.214555$$

$$Profit = \frac{1 - 0.002}{2} * \left[1 + 0.017077 - \frac{1}{1 + 0.002} + (1 + (-0.214555))(1 - 0.002 - \frac{1 + 0.008533}{1 - 0.002}\right] = 0.004597 = 0.4579\%$$

Initial investment amount on one exchange can be calculated using (3):

$$X = 30.56874 * 0.003449 = 0.10543158426\ BTC$$

Which means that the total investment amount on two exchange is:

$$2X = 2 * 0.10543158426 = 0.21086316852\ BTC$$

According to [2], average Bitcoin price on 7. and 8. August 2018 was $6500 which means that the total investment amount is approximately $1370. Considering the potential profit to be 0.4579%, 0.0009655 BTC ($6 as of 8. August 2018) of a real profit should have been made.

Following figures illustrate real orders and trades made on both exchanges:

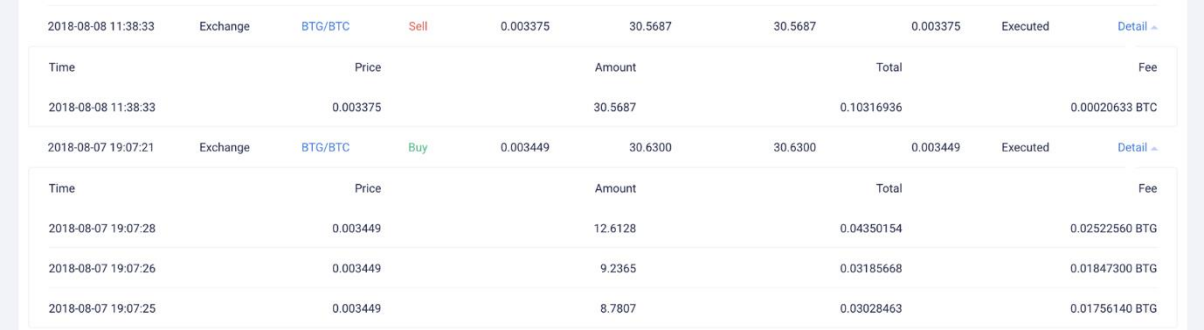

Figure 12. Trades on the exchange called “Huobi”.

PAIR	AMOUNT	PRICE	AVERAGE PRICE	CREATED	STATUS
BTG/BTC	30.568	0.003404	0.003403	8/8/2018 8:38:34 AM	EXECUTED @ 0.003403(0.3411): was PARTIALLY FILLED @ 0.003403(13.1279), PARTIALLY FILLED @ 0.003403(17.099)
BTG/BTC	-30.568	0.003508	0.00350832	7/8/2018 4:07:21 PM	EXECUTED @ 0.0035079(-16.2434016): was PARTIALLY FILLED @ 0.0035088(-14.3245984)

Table 5. Trades on the exchange called “Bitfinex”.

It can be noticed that on the exchange called “Huobi” 30.63 BTG was bought, 0.06126 of which went to pay the fees. It means that 30.56874 BTG was really got at the price of 0.003449 as mentioned above. Considering the amount of 30.63 BTG and the price of 0.003449, 0.10564287 BTC was invested. 30.568 BTG was afterwards sold at the price of

0.003375 resulting in final balance of 0.10316936 BTC. It can be calculated that the profit on the exchange called “Huobi” is negative, equal to -0.00247351 BTC.

On the exchange called “Bitfinex” 30.568 BTG was sold at the average price of 0.00350832. Considering the amount of 30.568 BTG and the price of 0.00350832, 0.10724232576 BTC was invested. Same amount of Bitcoin Gold (BTG) was afterwards bought at the average price of 0.003403, resulting in the final balance of 0.104022904 BTC. As the buy price is lower than the sell price, profit is positive, equal to 0.00321942176 BTC.

Final profit can be calculated comparing two final balances which is equal to 0.00074591176 BTC ($4.6 as of 8. August 2018). Profit became lower than theoretically expected as margin fees had not been considered and the prices on the exchange called “Bitfinex” slightly differ from the expected ones. Nevertheless, positive profit was attained.

4.2 Triangular arbitrage trading system results

Triangular arbitrage trading system found several arbitrage opportunities on 3. July 2018 starting from 08:44:23.The first found path was following:

$$BTC\ (binance) \rightarrow TRX(binance) \rightarrow TRX(huobi) \rightarrow USDT(huobi) \rightarrow USDT(binance) \rightarrow BTC(binance)$$

Price of *TRX/BTC* on the exchange called “*Binance*” was 5.85e-06, *TRX/USDT* on the exchange called “*Huobi*” was 0.037596 and *BTC/USDT* on the exchange called “*Binance*” was 6327.95. All prices were calculated from the given orders in the exchanges’ order books at that moment for the total volume of 4 BTC ($26400 as of 3. July 2018).

Following steps describe the required actions and their details:

1. Buy TRX for BTC on the exchange called “*Binance*”
    - Get 683076.9 TRX (considering 0.1% trading fee)
2. Withdraw TRX from the exchange called “*Binance*” to the exchange called “Huobi”
    - Get 683075.9 TRX (considering 1 TRX withdrawal fee)
3. Sell TRX for USDT on the exchange called “*Huobi*”
    - Get 25625.469434838 USDT (considering 0.2% trading fee)
4. Withdraw USDT from the exchange called “*Huobi*” to the exchange called “*Binance*”
    - Get 25615.469434838 USDT (considering 10 USDT withdrawal fee)

5. Buy BTC for USDT on the exchange called “Binance”
    - Get 4.043939 BTC (considering 0.1% trading fee)

It can be seen that the potential profit of 0.043939 BTC ($290) (or 1.09%) could have been achieved.

4.3 Future work

Although two different cryptocurrency arbitrage trading systems are already built as a result of this project, it is possible to add one more arbitrage trading method involving withdrawing assets from the exchange offering lower price to the one offering higher price and eventually selling the asset. Moreover, it is of a great significance to build a unified system which would notice any arbitrage opportunity and use either marginal trading, path finding brute-force algorithm or withdraw-and-sell method.

Such a unified system has plenty of possible commercial uses and is able to become a valuable software. Moreover, as plenty of people are looking for reliable trading systems, it is possible to bring in the investments and develop the system more professionally.

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