

# Automated Market-Making

Supervised by Professor Nick Whiteley

Joshua Acton

22nd March 2024

# Introduction

- How do financial markets work at the level of individual participants?
- How can we use stochastic control theory to model the behaviour of market participants?
- The Avellaneda-Stoikov Model
- Results on the statistical properties of the limit orderbook

# What is a financial market?

- Stocks, bonds, commodities, all manner of derivatives
- Multiple buyers, multiple sellers
- Prices determined by trading
- So how does trading actually occur inside the exchange?

# The limit orderbook

- Can either place *limit* orders or *market* orders
- *Limit* orders guarantee price but not execution
  - ▶ Limit orders can also be amended/updated for as long as they exist
- *Market* orders guarantee execution but not price
- *Spread* between best bid and best ask  $\rightarrow$  £0.02
- Can view the mid-price (here £1.00) as the “true” price

Side	Price /£	Volume
A	1.02	50
A	1.01	30
-	1.00	0
B	0.99	25
B	0.98	45

# The limit orderbook

After market buy order for 20 shares:

Side	Price / £	Volume
A	1.02	50
A	1.01	10
-	1.00	0
B	0.99	25
B	0.98	45

After another market buy order for 30 shares:

Side	Price / £	Volume
A	1.02	30
A	1.01	0
-	1.00	0
B	0.99	25
B	0.98	45

# Dealer considerations

Problem:

- What if no one wants to sell? resp. buy?
- What if buyers and sellers have wildly different price expectations?

Idea:

- Simultaneously place bid and ask limit orders → simultaneously buying and selling
- Enables other market participants to always have someone to trade against → “providing liquidity”
- Narrows the spread between bid and ask prices, decreasing implied cost of trading
- Dealer profits the small spread between buying and selling, multiplied across a large trading volume

Risks:

- Informed traders
- Inventory

# Modelling dealer behavior

If dealer accrues positive inventory:

- Want to sell more than buy
- Set lower ask price

If dealer accrues negative inventory:

- Want to buy more than sell
- Set a higher bid price

Now the maths...

# Stochastic Optimal Control

Following Pham (2009):

System:

$$dX_t = b(X_t, \alpha_t)dt + \sigma(X_t, \alpha_t)dW_t \quad (1)$$

Objective (Finite time horizon):

$$v(t, x) := \sup_{\alpha \in \mathcal{A}} \mathbb{E} \left[ \int_t^T f(s, X_s^{t,x}, \alpha_s) ds + g(X_T^{t,x}) \right] \quad (2)$$

Dynamic Programming Principle:

$$v(t, x) = \sup_{\alpha \in \mathcal{A}} \mathbb{E} \left[ \int_t^\theta f(s, X_s^{t,x}, \alpha_s) ds + v(\theta, X_\theta^{t,x}) \right] \quad (3)$$

Hamilton-Jacobi-Bellman Equation:

$$\frac{\partial v}{\partial t}(t, x) + \sup_{\alpha \in \mathcal{A}} [\mathcal{L}^\alpha v(t, x) + f(t, x, \alpha)] = 0 \quad (4)$$



# The Avellaneda-Stoikov model

Following Avellaneda & Stoikov (2008):

Model market mid-price as Brownian motion with variance  $\sigma^2$  (no drift)

$$dS_t = \sigma dW_t, \quad t \in [0, T]$$

The dealer quotes bid  $p^b$  and ask  $p^a$  with spreads  $\delta^b = s - p^b$  and  $\delta^a = p^a - s$  respectively. We assume that

- Market buy orders 'lift' the dealer's sell orders at Poisson rate  $\lambda^a(\delta^a)$
- Market sell orders 'hit' the dealer's bid orders at Poisson rate  $\lambda^b(\delta^b)$
- $\lambda$  is a decreasing function of  $\delta$

Have stochastic wealth and inventory:

$$dX_t = p^a dN_t^a - p^b dN_t^b \tag{5}$$

$$q_t = N_t^b - N_t^a \tag{6}$$

# The Avellaneda-Stoikov model

Objective function: Maximise expected utility of terminal wealth over possible bid/ask spreads  $\delta^a, \delta^b$

$$u(s, x, q, t) = \max_{\delta^a, \delta^b} \mathbb{E} \left[ -e^{-\gamma(X_T + q_T S_T)} | \mathcal{F}_t \right] \quad (7)$$

- HJB equation very difficult, maybe impossible, to solve analytically
- Through some asymptotic approximations we can work out an approximate solution in terms of our model parameters

# The Avellaneda-Stoikov model

We obtain the dealer's reservation price

$$r(s, q, t) = s - q\gamma\sigma^2(T - t) \quad (8)$$

which reflects a shift to the mid-price depending on our current inventory and model parameters, and our quote spread

$$\delta^a + \delta^b = \gamma\sigma^2(T - t) + \frac{2}{\gamma} \log \left( 1 + \frac{\gamma}{k} \right) \quad (9)$$

with  $\gamma$  and  $\sigma$  as before,  $k$  is a parameter from the orderbook describing how market order size impacts prices.

# Statistical properties of the limit order book

Poisson intensity  $\lambda(\delta)$  describes how likely a limit order is to be executed as a function of its distance to the mid-price. Need some statistics regarding:

- Overall frequency of market orders
  - ▶ For simplicity, assume constant  $\Lambda$
- Size distribution of market orders
  - ▶ “Econophysics”  $\implies$  power law  $f^Q(x) \propto x^{-1-\alpha}$
- Price impact of large market orders
  - ▶ “Econophysics”  $\implies$  either  $\Delta p \propto Q^\beta$  or  $\Delta p \propto \log Q$

Using the second result for price impact we obtain:

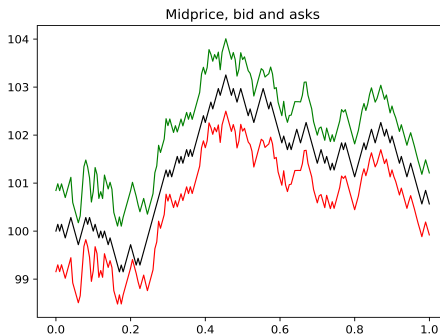
$$\begin{aligned}\lambda(\delta) &= \Lambda \mathbb{P}(\Delta p > \delta) = \Lambda \mathbb{P}(\log Q > K\delta) \\ &= \Lambda \mathbb{P}\left(Q > e^{K\delta}\right) \\ &= \Lambda \int_{e^{K\delta}}^{\infty} x^{-1-\alpha} dx \\ &= Ae^{-k\alpha\delta}\end{aligned}$$

# The Avellaneda-Stoikov model - Summary

- Estimate parameters from market data

At each timestep, given current inventory and estimated parameters:

- Compute reservation price  $r(s, q, t)$
- Compute spread  $\delta^a + \delta^b$
- Set quotes  $p^a = s + \frac{\delta^a + \delta^b}{2}$ ,  $p^b = s - \frac{\delta^a + \delta^b}{2}$



# Conclusion

- Stochastic control provides a useful framework through which to analyse the behaviour of market participants
- We can apply this framework to model the optimal behaviour of a dealer in financial markets
- This behaviour depends on the statistical properties of the particular market, which we can infer from market data

Thank you for your attention!

Questions?

email: `josh.acton.2021@bristol.ac.uk`